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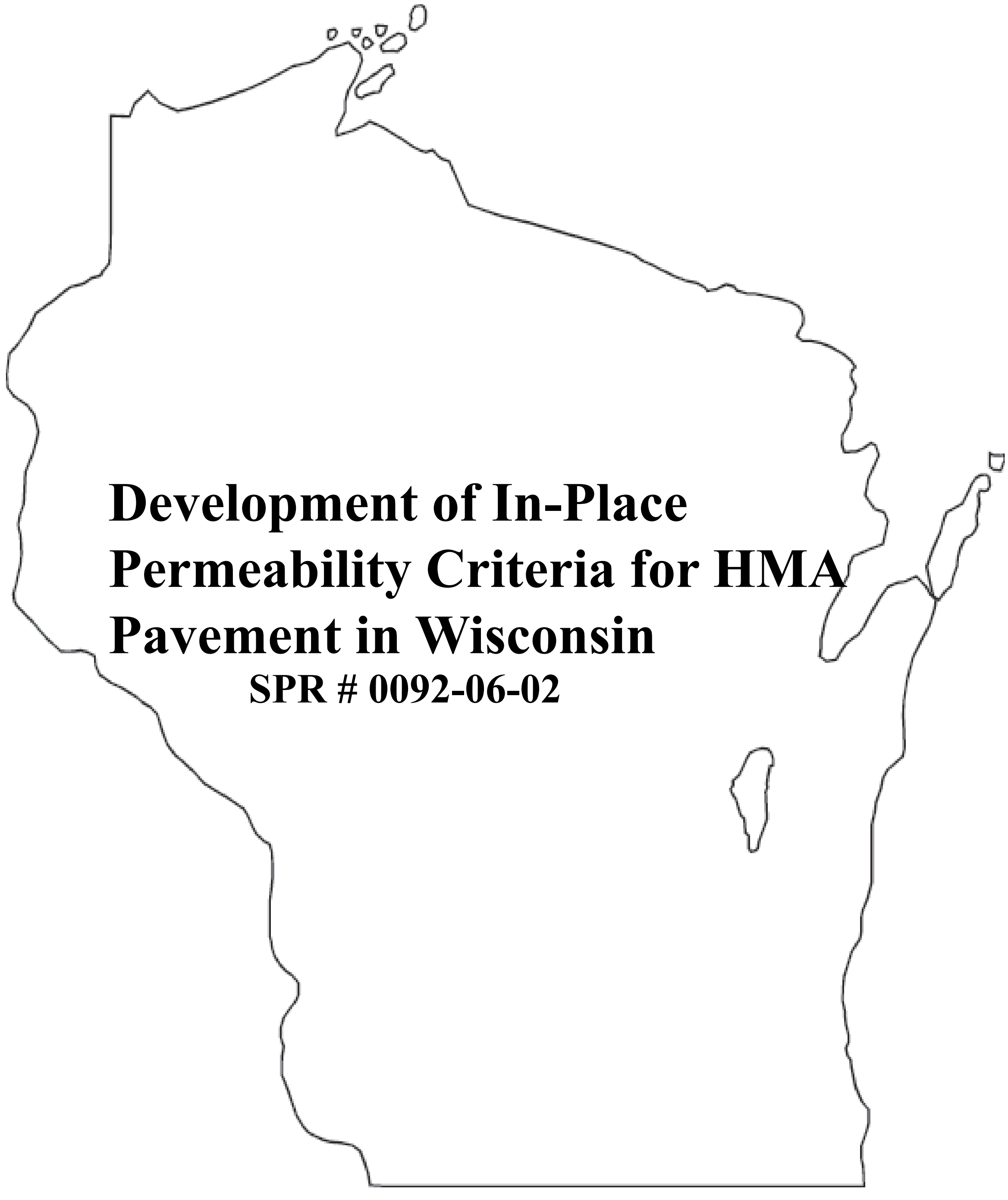

Development of In-Place Permeability Criteria for HMA Pavement in Wisconsin

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16. Abstract

The purpose of this study is the development of permeability and density acceptance criteria for HMA pavements in Wisconsin. The work detailed in this report is Phase I of II. Databases from the Pavement Management Unit of WisDOT were obtained for design, new construction reports, traffic, and performance data to assemble a profile of higher and lower performing pavements within a similar geographic region and truck traffic. Specific field tests on each project included water permeability with the NCAT device, air permeability with the ROMUS device, nuclear density, cores, and pavement distress surveys. Only fine-graded mixtures were tested.

In-service pavements were nearly impermeable, where water permeability rates ranged from 0 to 5 x 10E-5 cm/sec, and air permeability rates were a factor of 10 greater than water permeability. Water permeability between wheel paths were generally higher than in the wheel paths. In-service pavement density ranged from 92% to 99%. Air permeability trended downward with an increase in density, while water permeability had no discernible trend.

A methodology for developing design criteria for permeability and density based on preliminary findings was presented. Defining a specific criteria requires establishing a target PDI to yield an expected design permeability, which in turn specifies as-built density at construction. Similarly, the target PDI/year determines the as-built density, to achieve the target value. Based on limited data, it was not possible to establish definitive criteria for permeability and density. A work plan was proposed for Phase II of the study to produce performance models that will establish specific criteria. Phase II will require a long-term study of about 5 years. As-built construction data will be collected on projects throughout the state having varying density requirements, then performance data are collected and monitoring every other year until the pavement reaches 8 years of age.

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EXECUTIVE SUMMARY

The purpose of this study was Phase I in the development of permeability and density acceptance criteria for HMA pavements in Wisconsin, where results also aided in the development of mixture-specific permeability relationships that can be utilized by pavement designers to better describe the in-place permeability and density of HMA pavement layers. To achieve these objectives, literature were reviewed, a field experiment was designed and conducted, then data were analyzed to develop a criteria framework.

After a detailed literature review, only one source was found that related in-place permeability to actual field performance, a 1962 California Division of Highways study. Findings from the study suggested that water may contribute to possible failure of the pavement by acting as the agent for transporting base dust and clay fines into the interstices of the pavement mixture, and this action may contribute to the rapid hardening of the binder, especially in the lower part of the pavement. Field tests indicated that initial compaction, together with some form of pneumatic rolling, are very important factors in reducing pavement permeability. Also, permeability may continue to decrease immediately after construction and will definitely decrease for pavements laid during the normal paving season when subjected to traffic during the summer months. However, permeability may not decrease if the pavement is constructed during the cooler fall months.

Databases from the Pavement Management Unit of WisDOT were obtained for design, new construction reports, traffic, and performance data to assemble a profile of higher and lower performing pavements within a similar geographic region and truck traffic levels. Pavement age ranged from 3 to 11 years, and both warranted and non-warranted projects were selected. Twenty projects were selected for testing, and each included 20 test sites, where 10 test sites were within the wheel path and 10 test sites were between the wheel paths. Specific field tests on each project included water permeability with the NCAT device, air permeability with the ROMUS device, nuclear density, cores, and pavement distress surveys. Only fine-graded mixtures were tested.

In-service pavements were nearly impermeable, where water permeability rates ranged from 0 to 5 x 10E-5 cm/sec, and air permeability rates were a factor of 10 greater than water permeability. Water permeability between wheel paths were generally higher than in the wheel paths. In-service pavement density ranged from 92% to 99%. Air permeability trended downward with an increase in density, while water permeability had no discernible trend. When surface layer thickness was compared to in-service pavement density, no trend was observed. There was no clear relationship between permeability and surface layer thickness.

Water permeability was analyzed with respect to project variables and mixture-specific variables. Age did not directly influence permeability, where pavements 6 years of age were more permeable than 3- and 4-year old pavements. Higher traffic levels, as measured by daily vehicle traffic and daily truck traffic, appeared to reduce permeability. Percentage passing 75-um sieve had no impact on permeability. Blend percentage of manufactured sand did not appear to have a definitive trend on permeability, however, a positive relationship between water permeability and FAA was shown. Pavements designed at both 3.5% air voids (pre-

Superpave) and 4% air voids (current practice) had no effect on permeability. Voids in mineral aggregate (VMA) had a positive relationship with permeability, while voids filled with binder (VFB), Ndes, and asphalt content did not have an affect on permeability.

Pavement performance was analyzed with respect to both density and permeability. The data found that pavements having a lower as-built density, generally below 92%, performed at a lower level (higher PDI value and more cracking). No clear trend was observed for PDI and in-service density, and no definitive trend was found between rut depth and both as-built and in-place density. No relationship was found between density and edge raveling.

With respect to performance and permeability, the pavements were nearly impermeable and no relationship was shown. Rut depth did not have a definitive relationship with permeability, and no relationship was found between permeability and both transverse cracking extent and severity. Water permeability did not have an effect on longitudinal cracking and edge raveling based on the available data

A methodology for developing design criteria for permeability and density based on preliminary findings was presented. Defining a specific criteria requires establishing a target PDI (as defined by preventive maintenance intervention, economic analysis, or other means) to yield an expected design permeability, which in turn specifies as-built density at construction. Similarly, the target PDI/year determines the as-built density, to achieve the target value. The maximum of the two values is chosen as the controlling density to yield the desired PDI and corresponding design permeability. The controlling density is further used to select the critical mix design property as represented, for example, by the VFB. Other mixtures variables can easily be included, once supporting data are available and modeled.

Based on limited data, it was not possible to establish definitive criteria for permeability and density. A work plan was proposed for Phase II of the study to produce performance models that will establish specific criteria. Phase II will require a long-term study of about 5 years. As-built construction data will be collected on projects throughout the state having varying density requirements, then performance data are collected and monitoring every other year until the pavement reaches 5 years of age.

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CHAPTER 1 INTRODUCTION

1.1 Background and Problem Statement

The placement of impermeable HMA pavements has been recognized as an effective means to protect against rapid oxidation of the binder materials and excessive moisture damage in HMA pavement layers. National studies have shown that the desired air void content of in-place HMA pavements is below 8% and that the desired permeability is below 150×10^{-5} cm/sec. These critical values for in-place air voids and permeability were based solely on their relationship and are only empirically derived. Intuitively, an excessive amount of permeability significantly increases the potential for poor performing pavements, however the relationships of both air voids and permeability with actual performance have not been clearly defined.

1.2 Objective

The objectives of this research study are to:

(1) Determine the in-place permeability and density of HMA pavements that have documented performance records;

(2) Use this information to enhance the understanding of the inter-relations between HMA mixture properties, in-place permeability and pavement performance; and

(3) Establish target permeability and density values suitable for use within contract specifications.

1.3 Background and Significance of Work

In 2002, WHRP sponsored a statewide evaluation of in-place density and permeability of Superpave mixtures constructed with varying thickness to nominal maximum aggregate size ratios (Russell et al. 2004). While the objectives of this study included the development of recommended target permeability values for use during construction, insufficient performance data was available to accurately establish target values that could be validated for inclusion into WisDOT specifications. The study recommended that target permeability and density values ultimately be established from in-service pavements with recorded performance histories. Based on collected data for fine-graded Superpave mixes, a specified minimum density of 93.8% would be required to limit permeability to 150×10^{-5} cm/sec (Russell et al. 2004). For coarse-graded Superpave mixes, the research data did not support the establishment of minimum acceptable densities based solely on permeability criteria.

An opportunity exists to define what level of permeability and density yields an acceptable level of performance by collecting data from a range of HMA pavements. A total of 68 warranted HMA pavements have been constructed in Wisconsin between 1995 and 2004. These pavements represent a valuable data set that may be researched to develop relationships between in-place mixture properties and pavement performance. In-service non-warranted pavements may also provide useful data in this determination. By means of a carefully conducted field study of these pavements, permeability acceptance criteria may be developed to enhance future pavement performance.

While the primary focus of this research is the development of permeability acceptance criteria for HMA pavements in Wisconsin, it anticipated that the results of this research will also aid in the development of mixture-specific permeability relationships that can be utilized by pavement designers to better describe the in-place permeability and density of HMA pavement layers. The developed relationships should be capable of incorporating readily obtainable mixture design data for the characterization of constructed HMA layers. This study is also expected to provide recommendations for possible revisions to the WisDOT construction specifications for HMA pavement layers.

1.4 Benefits

The potential benefits of this study include:

- Yield quantified relationships and models between in-place permeability, density, mixture characteristics, and performance for a full range of in-place HMA pavements in Wisconsin.

- Broaden WisDOT and industry knowledge of the relationships between design, construction, traffic and environmental variables that are believed to influence the performance of HMA pavements.

- Enhance the understanding of internal HMA pavement properties which will lead to larger benefits, in the form of increased performance levels of HMA pavement systems.

- Move towards fact-based decision-making and cost savings by creating proactive awareness of options or changes to design and construction activities, materials, and methods to improve quality, and overall enhanced knowledge of the pavement system.

- Enhance educational opportunities to UW-Platteville engineering students, allowing them to translate their knowledge of in-place performance characteristics of HMA pavements to the betterment of transportation agencies in the Midwest.

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

A literature review was conducted to find all information related to in-place permeability and in-situ pavement performance, by searching the Transportation Research Information Services (TRIS) database. After a detailed search, one literature source was found that related in-place permeability to actual field performance. A California Division of Highways study suggested that water may contribute to possible failure of the pavement by acting as the agent for transporting base dust and clay fines into the interstices of the pavement mixture, and this action may contribute to the rapid hardening of the binder, especially in the lower part of the pavement (Zube 1962). Field tests indicated that initial compaction, together with some form of pneumatic rolling, were very important factors in reducing pavement permeability. Also, permeability may continue to decrease immediately after construction and will definitely decrease for pavements laid during the normal paving season when subjected to traffic during the summer months. On the other hand, pavements placed during the late fall or winter must rely on adequate initial compaction because no further decrease in permeability may be expected before the following summer. Asphalt pavements or seal coats should not be placed in the late fall or during the winter months.

2.2 Studies Investigating Field Permeability

Table 2.1 summarizes key findings from previous field studies of those factors investigated for field permeability. These factors were investigated during field component of this study (Phase I of II).

Table 2.1 Key Findings on Permeability from Prior Field Studies

Year (1)	Study or Publication (2)	Key Findings related to Permeability (3)
2004	Wisconsin Highway Research Program Project 0092-04-02c, “Effect of Pavement Thickness on Superpave Mix Permeability and Density,” University of Wisconsin.	• Base type, aggregate source, gradation, and Ndes all influence field density and permeability. • Coarse-graded mixes were more permeable than fine-graded mixes for equivalent density. • Fine-graded limestone-sourced mixtures compacted on PCC, and those designed at higher Ndes levels, were more permeable than other mixes. • Gradation ratios may have an effect on permeability: (%P12.5mm - %P9.5mm)/ (%P4.75mm-%P2.36mm) • Layer thickness, and thickness/NMAS ratio did not have a clear relationship with permeability in fine-graded mixes.

Table 2.1 (cont.) Key Findings on Permeability from Prior Field Studies

Year (1)	Study or Publication (2)	Key Findings related to Permeability (3)
2004	NCHRP 9-27, "Relationship of HMA In-Place Air Voids, Lift Thickness, and Permeability", NCAT	• In-place void content is the most significant factor impacting permeability. • As the coarse aggregate ratio increases, permeability increases. • Permeability decreases as VMA increases for constant air voids. • Variability of permeability among mixtures is very high with some more permeable at 8 to 10% voids and others not. • In-place air voids should be between 6 and 7% or lower to ensure that permeability is not a problem. This appears to be true for a wide range of mixtures regardless of NMAS and gradation.
1999	Maine DOT with NCAT, "Evaluation of Permeability of Superpave Mixes in Maine"	• NMAS and thickness/NMAS ratio affect permeability.
1998	Florida DOT, "Investigation of Water Permeability of Coarse Graded Superpave Pavements"	• Coarse-graded mixes can be permeable to water even when in-place air voids are less than 8%.
1998	Florida DOT, "Superpave Field Implementation: Florida's Early Experience"	• Layer thickness can influence density, and subsequently, permeability. • Increased layer thickness has the ability to enhance pavement density, thus reducing permeability.
1998	Arkansas Superpave Symposium, "Experience with Superpave Pavement Permeability"	• Thickness/NMAS ratio of 4.0 is preferred to achieve desired density and minimize permeability.
1988	University of Arkansas, "Asphalt Mix Permeability"	• Particle size distribution, particle shape, and density (air voids or percent compaction) affect permeability.
1962	California Division of Highways	• Adequate compaction is important in reducing permeability. • Fog seals will decrease the permeability but will not prove effective if the initial permeability is high.

CHAPTER 3 INVESTIGATION OF DATABASES

3.1 Introduction

Databases from the Pavement Management Unit of WisDOT were obtained for design, new construction reports, traffic, and performance data. The reason for collecting these databases was to assemble a profile of higher and lower performing pavements within a similar geographic region, and having similar levels of truck traffic. Then, an initial selection of 20 projects was made for field evaluation. The following sections describe the databases, initial project selection, and final projects used for data collection.

3.2 Database Descriptions

The following databases in Table 3.1 were accessed with assistance from the WisDOT Pavement Management Unit.

Table 3.1 Databases Accessed in Study

Database (1)	Description (2)
Meta Manager	This database compiles traffic data and forecasts anticipated traffic levels. Traffic data from each of the 5 WisDOT regions were combined into one dataset to yield 20,536 pavement segments (0.01 to about 2 miles in length). Key data fields obtained were highway number, pavement sequence number, Reference Point (RP), termini of segment, pavement type, functional class, number of lanes, projected AADT for 2006, and percent trucks.
Pavement Inventory Files (PIF).	Descriptions and pavement distress data for each RP segment were obtained, including PDI, IRI, and both extent and severity of individual pavement distresses (block cracking, rutting, edge raveling, etc.). This database also included highway number, termini description, directional lane of measurement, year of measurement, district number, and county.
New Construction Reports	Attributes of projects constructed in a given year are detailed, including such fields as prime contractor, thickness of HMA layers paved, base preparation (milling, pulverize, undisturbed, etc.), length of paving, and project identification number. This database was used to verify the paving year of RP segments in the Meta Manager and PIF databases.
Construction Materials Tracking System	Test results and construction reports from WisDOT projects constructed from 2000 to present are provided in PDF format.
As-Built Construction Data	WisDOT regions and contractors were asked to provide as-built construction data from projects, including the Job Mix Formulas, actual mix properties from running average calculation sheets, and pavement density. Data were in paper format and required hard entry for this study.

The Meta Manager and PIF databases were merged by pavement sequence number (e.g., Reference Point) to yield a single composite database for every pavement segment in Wisconsin under the jurisdiction of WisDOT. The merged database was then reduced to pavement segments that were either Type 1 (HMA paved over asphalt concrete or CABC base) or Type 3 (HMA paved over PCC base). Road Mix (Type 2) and all PCC pavements were deleted from the database yielding 14,361 Type 1 or 3 pavement segments for consideration. These individual segments were then combined by similar termini (beginning and ending points) and the performance data within each termini were averaged, including the International Roughness Index (IRI), Pavement Distress Index (PDI), average rutting, and Present Serviceability Index (PSI). The number of segments (or Reference Points) that were averaged ranged from 1 to 16. Segments having only 1 segment were eliminated from consideration, since this single data point does not provide a complete understanding of overall performance.

3.3 Initial Project Selection

Since warranted pavements are believed to perform better than non-warranted pavements, the database was divided into warranty and non-warranty asphalt pavements. Three age groups were considered in this selection including 10-, 7-, and 5-year old pavements (relative to 2005). Pavements 5 to 10 years in age were targeted to understand performance (1) when terminal pavement serviceability can be approximated for future treatments and/or rehabilitation, (2) prior to sealcoats or patching usually after the 10-year age, and (3) during a period of accelerated distresses potentially from water permeability. Additionally, the 10-year selection was made to provide understanding of permeability impacts on field performance of pavements constructed during the beginning of warranty practices in Wisconsin (i.e. 1995). The 7-year old pavements were selected to represent pavements constructed at the beginning of the implementation of SuperPave mix design practice in Wisconsin, while the 5-year old pavements were chosen to represent pavements that have just moved out of the warranty stage and no longer under the jurisdiction of the contractor. During this process, the research team was advised by the WisDOT Pavement Management Unit that coring pavements under warranty could create liability concerns and should be avoided. In addition, 5-year old pavements were selected to allow distresses to appear after repeated truck loading and exposure to the environment.

A review of the WisDOT databases revealed that the majority of warranty projects were performed on roadways functionally classified as Class 10 (rural principal arterial) and Class 20 (rural minor arterial). Hence, the selection was made for only these two functional classifications. Based on the number of projects within the age groups, three projects were selected to represent the 10-year olds, another set of three for the 7-year olds, and four for the 5-year old projects. When the number of warranty projects in a particular age group were few (e.g., three for the 10-year category) all were included in the overall selection. If several projects occurred in a particular age group (e.g. as in both the 5 and 7-year groups), projects were selected to provide a balance between poor and good pavements as indicated by the average rutting and pavement distress values. The database provided data on four performance indicators including the IRI, PDI, average rutting, and PSI. In addition, extent and severity of individual pavement distresses were evaluated (longitudinal cracking, edge raveling, etc.)

It has been well documented in the literature that several factors affect permeability, such as aggregate gradation and density. However, the literature review yielded no investigations relating field performance and permeability. Since the principal focus of the Phase I investigation is the relationship of performance and permeability, several performance indicators were evaluated at this stage of the study, including, the composite PDI value, IRI, rutting, block cracking, longitudinal cracking, and edge raveling. Rutting distorts the pavement cross-section and has the potential to trap water when it is of significant depth. The standing water can facilitate the initiation or progression of moisture-related distresses, thus causing water to permeate the pavement. The PDI was used to judge the overall condition of the pavement in terms of all distresses. Edge raveling may be an indicator of permeability-related distress, and was assessed during project selection. Transverse cracking was not considered a primary indicator, since asphalt binder in pre-Superpave pavements were not designed for low-temperature thermal cracking, and some projects produce reflective cracking from the lower base, compounding the investigation.

Once the warranty projects were selected, poor-performing non-warranty projects of similar age and functional class were identified. Table 3.2 provides the preliminary list of warranty and non-warranty pavement segments that were considered for selection. Projects are grouped by 1995, 1998, and 2000 constructions years, and each group sorted by PDI. Projects in light gray (or red with color printer) are warranty, while those in black are non-warranty. Cracking-related distresses included the extent and severity. For example, 100 lineal feet of longitudinal cracking at severity level 3 would be designated '100-3'.

Table 3.2 Preliminary Project List

Hwy	County	Termini	Const Year	No. RPs	Pvmt Type	Func. Class	AADT	% Trk	ADTT	PDI	Rut, ave in.	IRI in./mi.	Blk Crk	Tran Crk	Long Crk	Edge Crk Rav	Edge Crk Fill.
11	ROCK	ORFORDVILLE-FOOTV	1995	5	1	10	5942	14	832	14	0.08	1.03		05-1	100-1		1
45	LANGLADE	CTH B – CTH J	1995	7	1	10	4796	10	480	16	0.23	1.14		05-1	100-1		1
85	EAU CLAIRE	WEST COUNTY LINE -	1995	4	1	20	3160	10	316	27	0.09	1.42		05-1	200-1		
173	WOOD	MONROE CO LINE – S	1995	4	1	20	1890	12	227	42	0.28	1.82		10-1	200-1		1
45	LANGLADE	CTH J - LANGLADE/ON	1995	11	1	10	4841	10	484	46	0.24	1.31	74-1	10-1	100-3		1
173	JUNEAU	MONROE CO LINE – S	1995	9	1	20	2056	12	247	48	0.27	1.53		11-1	100-3		2
70	BURNETT	CTH W/FALUN – S JCT	1995	5	1	10	4726	10	473	55	0.34	1.23		11-3	200-1		2
10	TREMPEAL.	/10TH ST/CITY OF OSS	1995	4	1	20	7833	8	627	57	0.18	1.47		10-3	200-1		2
17	LINCOLN	STH 64 – HAYMEADOV	1995	7	1	20	4670	6	280	57	0.22	1.95		11-3	200-1		
59	GREEN	CTH S - ALBANY	1995	5	1	20	1758	10	176	60	0.15	1.37	75-1	10-3	200-3		1
97	MARATHON	MYRTLE ST/STRATFRI	1995	3	1	10	5947	8	476	62	0.17	1.47	75-1		100-1		2
10	TREMPEAL.	ELEVA - OSSEO	1995	6	1	20	3085	8	247	64	0.27	1.75		10-1	200-3		2
59	GREEN	ALBANY – STH 104	1995	2	1	20	2455	10	246	64	0.22	1.77	74-1	05-3	100-1	1	1
97	MARATHON	STRATFORD (SOUTH :	1995	2	1	10	7120	8	570	68	0.15	1.54	49-1	10-3	100-1	1	1
27	BAYFIELD	W JCT STH 77 – CTH N	1995	2	1	20	1070	6	64	76	0.25	2.13		10-1	200-3		
60	CRAWFORD	E JCT USH 61 – STH 8	1998	2	1	20	1650	10	165	8	0.09	1.21					2
60	RICHLAND	E JCT USH 61 – STH 8	1998	1	1	20	1470	10	147	8	0.09	1.34					2
95	JACKSON	BLAIR - HIXTON	1998	9	1	20	2680	8	214	11	0.15	1.08		05-1	100-1		1
35	ST. CROIX	E JCT STH 64/SOMERS	1998	6	1	20	6090	7	426	12	0.07	1.28		05-1	100-1		2
60	SAUK	CTH B - CTH O	1998	4	1	20	3600	10	360	10	0.21	1.23					2
35	PIERCE	USH 63 – CTH OO	1998	4	1	20	2485	6	149	16	0.24	1.07					2
13	BAYFIELD	1.01N CTH C/WASHBU	1998	11	1	20	5854	9	527	16	0.20	1.33		10-3	100-1	1	2
35	POLK	.25N STH 48/FREDERI	1998	5	1	20	4192	7	293	17	0.19	0.99		05-1	200-2		2
35	BURNETT	SOUTH CO LINE – S J(	1998	3	1	20	3880	7	272	17	0.21	0.94		10-1	100-1		1
97	MARATHON	.10S CTH P - .18N ELD	1998	5	3	10	3420	8	274	21	0.24	1.33		05-1	100-1		2
89	JEFFERSON	LENIUS RD – ECPL W/	1998	2	1	20	3180	10	318	21	0.19	1.34			100-1		1
63	POLK	SOUTH COUNTY LINE	1998	16	1	10	4593	10	459	23	0.26	0.93		05-1	100-1		2
63	WASHBURN	S JCT CTH B/SHELL L/	1998	5	3	10	5910	10	591	24	0.21	1.27		05-1	200-1		2
93	TREMPEAL.	ELK CREEK - ELEVA	1998	13	1	10	3331	12	400	29	0.11	1.19		11-1	200-1		1
45	ONEIDA	E JCT USH 8/MONICO	1998	13	1	10	2642	10	264	29	0.12	1.05		10-1	200-1		1
13	BAYFIELD	CTH I/BAYFIELD – E J(	1998	5	1	20	2594	9	233	36	0.39	2.14		10-3	100-1		2
55	LANGLADE	CTH T – NORTH COUN	1998	4	1	20	1783	7	125	37	0.12	1.27		10-3	200-3	1	1
11	GREEN	SKINNER CRK - 9TH A	1998	5	1	10	6072	8	486	40	0.12	1.26			300-3		1
66	PORTAGE	E JCT CTH J – STATE	1998	2	1	20	3870	10	387	41	0.08	1.51	49-1	10-1	200-1		1
51	IRON	CTH J – MOOSE LAKE	1998	5	1	10	2654	10	265	51	0.12	1.30		10-1	200-3		1
64	ST. CROIX	E JCT STH 35 - 95TH S	1998	5	3	20	7700	10	770	51	0.14	1.60		10-3	200-3		1
13	WOOD	CRANBR CR/WI RAPIE	2000	14	1	20	6296	9	567	6	0.06	1.04		05-1	100-1		
64	CHIPPEWA	STH 124 – CTH E	2000	3	1	20	2030	10	203	8	0.10	0.98		05-1	100-1		2
73	TAYLOR	SOUTH COUNTY LINE	2000	7	1	20	1444	10	144	8	0.09	1.43			100-1		
14	RICHLAND	RICHLAND CENTER-E/	2000	6	1	10	5883	9	529	9	0.09	0.88			100-1		2
73	TAYLOR	N JCT STH 64 - HANNI	2000	8	1	20	986	10	99	11	0.10	1.53					
131	MONROE	STH 71 – TOMAH (SOU	2000	8	1	20	3110	7	218	15	0.08	0.82			200-1		
129	GRANT	LANCASTER BYPASS	2000	3	1	10	3750	8	300	18	0.28	1.24			100-1		2
77	WASHBURN	SOO LINE RR – N JCT	2000	7	1	20	1664	10	166	18	0.21	1.03		05-1	200-1		2
80	GRANT	N JCT STH 11 – CUBA	2000	2	1	20	5025	10	503	23	0.26	0.95			100-1		1
8	PRICE	LUSTILA RD – CTH YY	2000	7	3	10	2990	8	239	26	0.23	0.96		10-1	200-1		1
8	LINCOLN	CTH YY – MCCORD RI	2000	4	3	10	2860	8	229	31	0.25	1.07		10-1	200-1		1
8	ONEIDA	CTH YY – MCCORD RI	2000	3	3	10	3040	8	243	32	0.23	1.03		10-1	200-1		1
12	EAU CLAIRE	AUGUSTA (W JCT CTH	2000	3	1	20	5020	6	301	38	0.14	1.35		10-1	100-3		2
58	JUNEAU	.72N MILE BLUFF RD -	2000	2	1	20	3235	10	324	41	0.10	1.35		11-1	200-1		
58	JUNEAU	CHAPEL RD – STEINEI	2000	2	1	20	1725	10	173	50	0.10	1.47	75-1	11-1	200-1	1	1
12	EAU CLAIRE	CTH R – W JCT CTH G	2000	1	1	20	6450	6	387	71	0.14	1.55		10-1	100-3		2

From the list in Table 3.2, the non-warranty projects were chosen either along the same route in the immediate vicinity, or in the same geographical region. This was purposely done to block the effects of climate and variability in traffic patterns on pavement performance. In addition, selection of projects closer to warranty projects reduced travel distance from one project to another and helped to effectively manage field data collection resources. Thus, the non-warranty projects were subjected to constraints imposed by the warranty projects.

Table 3.3 shows the selected projects for field evaluation. The projects are paired by rows to show the difference in rutting and PDI between projects of similar geographic region and age. Two pairs of 10-year old projects having different truck levels (ADTT), and purposely offset during the pairing process, included STH 85 / USH 10 and STH 11 / STH 59. There were several poorer performing projects in the northern areas of the state, but no warranty projects were in the vicinity or had similar truck loading (Bayfield and Iron Counties).

Table 3.3 Initial Projects Selected for Field Evaluation of Permeability

Hwy	County	Termini	Functional Class	Surface Age (years)	Rut depth (in)	PDI	Warranty Project	
							Yes	No
131	MONROE	STH 71-TOMAH	20	5	0.08	15	√	
58	JUNEAU	CHAPEL RD-STEINER RD	20	5	0.10	50		√
73	TAYLOR	N JCT STH 64-HANNIBAL	20	5	0.10	11	√	
77	WASHBURN	SOO LINE RR – N JCT STH 27	20	5	0.21	18		√
14	RICHLAND	RICHLAND CENTER-EAST COUNTY LINE	10	5	0.09	9	√	
129	GRANT	LANCASTER BYPASS	10	5	0.28	18		√
64	CHIPPEWA	STH 124 – CTH E	20	5	0.10	8	√	
12	EAU CLAIRE	AUGUSTA (W JCT CTH G - ECPL)	20	5	0.14	38		√
35	ST. CROIX	E JCT STH 64/SOMERSET – NORTH CO LINE	20	7	0.07	12	√	
35	POLK	.25N STH 48/FREDERIC - NORTH CO LINE	20	7	0.19	17		√
95	JACKSON	BLAIR - HIXTON	20	7	0.15	11	√	
35	PIERCE	USH 63 – CTH OO	20	7	0.24	16		√
60	RICHLAND	E JCT USH 61 – STH 80	20	7	0.09	8	√	
60	SAUK	CTH B - CTH O	20	7	0.21	10		√
85	EAU CLAIRE	WEST COUNTY LINE - .66W STH 37	20	10	0.09	27	√	
10	TREMPEALEAU	/10TH ST/CITY OF OSSEO	20	10	0.18	57		√
45	LANGLADE	CTH B – CTH J	10	10	0.23	16	√	
45	LANGLADE	CTH J - ANGLADE/ONEIDA CO LINE	10	10	0.24	46		√
11	ROCK	ORFORDVILLE-FOOTVILLE	10	10	0.08	14	√	
59	GREEN	ALBANY – STH 104	20	10	0.22	22		√

3.4 Final Project Selection

During field testing on the first six projects in the study, minimal water permeability was observed, with values generally below 1x10E-5 cm/sec. Water in the top standpipe of the permeameter would drop 1 or 2 cm in a period of 2 minutes, and in some cases, there was no drop equating to zero permeability. Density values were typically 95% or higher, and the difference in density between wheel path and between path was about 0 to 3%. This type of data provided little resolution to clearly decipher if permeability had an effect on performance. Thus, it was decided to test newer pavements built from 2000 to 2003 based on the following considerations:

- Less densification in and between wheel paths to understand density change from new construction to in-service period;
- Less densified pavements would be more permeable;
- Paved during implementation of Superpave, and recommendations would be easier to implement (projects paved before 2000 used the Marshall mix design method);
- Projects from the original WHRP permeability-density study (Russell et al. 2004) could be tested to understand the change in both permeability and density after traffic loading and aging, and aligned with the measured distresses. Several projects in the original study where surface layers were tested include STH 21 near Omro, STH 23 near Montello, USH 8 near Rhinelander, and STH 110 frontage road near Winneconne. This scope of this study was limited to surface layers.; and
- There may be less severity of distresses. Older pavements have more distresses, and the test of whether permeability is a factor would be more difficult.

Table 3.4 describes the actual projects used for field evaluation. The same selection criteria from the initial project selection were used to develop this final list. The following chapter describes the field testing plan.

Table 3.4 Final Projects used for Field Evaluation of Permeability

Hwy	County	Termini	Func-tional Class	Surface Age (years)	Rut depth (in)	PDI	Warranty Project	
							Yes	No
11	ROCK	ORFORDVILLE-FOOTVILLE	10	10	0.08	14	√	
59	GREEN	ALBANY – STH 104	20	10	0.22	22		√
60	CRAWFORD	E JCT USH 61 – STH 80	20	7	0.09	8	√	
60	SAUK	CTH B - CTH O	20	7	0.21	10		√
14	RICHLAND	RICHLAND CENTER-EAST COUNTY LINE	10	5	0.09	9	√	
129	GRANT	LANCASTER BYPASS	10	5	0.28	18		√
131	MONROE	STH 71-TOMAH	20	5	0.08	15	√	
58	JUNEAU	CHAPEL RD-STEINER RD	20	5	0.10	50		√
64	CHIPPEWA	STH 124 – CTH E	20	5	0.10	8	√	
12	EAU CLAIRE	AUGUSTA (W JCT CTH G - ECPL)	20	5	0.14	38		√
13	DOUGLAS	TOWN RD – CTH F	20	5	0.11	8		√
77	WASHBURN	SOO LINE RR – N JCT STH 27	20	5	0.21	18		√
23	MARQUETTE	MONTELLO-PRINCETON	10	3	0.04	11		√
96	WAUPACA	STH 110 – TEWS DR.	20	3	0.04	25		√
22	WAUPACA	MANAWA-USH 45	20	3	0.07	4		√
96	BROWN	STH 32/57 – CTH G	20	5	0.06	26		√
8	ONEIDA	W. CO. LINE – STH 47	10	2	0.06	11		√
47	VILAS	CTH D – LAC DU FLAMBEAU	20	2	0.10	29		√
32	FOREST	S. CO. LINE - WABENO	20	2	0.07	4	√	
70	FOREST	W. CO. LINE – STH 55	20	2	0.13	4		√

CHAPTER 4 EXPERIMENTAL DESIGN

4.1 Introduction

A field experiment was developed to address the study objectives, while working within the constraints of available resources. The experiment specified data from 20 in-service HMA pavement segments constructed since 1995. Ten of the pavement segments were considered higher performing, while ten were lower performing. The project selection described in the previous chapter successfully controlled the effects of traffic and the environment, so that the research objectives could be addressed in a straight-forward manner without their confounding effects.

Data specified on each of the 20 segments included:

- Nuclear Density = 20 sites;
- Water Permeameter = 8 sites;
- Air Permeameter = 20 sites;
- Cores = 8 sites (2 sites on final 10 projects);
- Pavement Distress Survey = one 528-foot length segment; and
- As-built construction data.

The reason for sampling only 8 sites with the water permeameter and cores was to balance the sample size with an allotted budget for a half-day testing on each segment. The purpose for the 20 air permeameter and nuclear density sites was to strengthen the data set, since the number of water permeability and core test sites was limited.

4.2 Test Equipment

The following test equipment used in the field investigation:

- NCAT water permeameter;
- ROMUS air permeameter;
- CPN MC-3 nuclear density gauge;
- Core drill, generator, and both 4-inch and 6-inch diameter core bits;
- Pavement Distress Index (PDI) survey manual and equipment, including 6-foot long straightedge to measure rutting; and
- Traffic control subcontracted to host county highway department. Selection of predominantly Rural Minor Arterial (Function Class 20) pavements for this field investigation provided added safety to the county crews and research team with AADT levels generally below 8,000.

4.2.1 Water Permeability Testing

The NCAT water permeameter was centered within the rectangular base used for nuclear density testing, sealant was applied to a rubber gasket between the pavement and permeameter base, two 50-lb weights were added to prevent uplift force from the water head. The NCAT permeameter was filled and allowed to sit on the pavement for 2 minutes prior to conducting tests. Several trials were conducted at each test site for repeatability information and to average the test results.

Prior to field testing, there was a concern about the seal between the water permeameter and in-service pavement, particularly on rutted or rough-textured surfaces, so a evaluation of rubber gaskets was conducted at the Reichel-Korfmann Company in Milwaukee on June 21st. These gaskets were able to successfully seal the water permeameter throughout field testing. Table 4.1 provides the attributes of these gaskets, along with the silicone sealant. Figure 4.1 provides an illustration of silicone sealant applied to the rubber gasket before seating on the pavement surface. Figures 4.2 and 4.3 illustrate filling the NCAT water permeameter and measuring the falling head, respectively.

Table 4.1 Rubber Gasket and Sealant Attributes

Gasket Attributes	Sealant Attributes
• American National Rubber, Neoprene-EPDM-SBR blend. • Closed cell rubber sponge, 9-1/4" square, 3/4" thick, with 5-1/2" diameter hole machine cut. A 6-inch machined hole would match the inside diameter of the permeameter, but the 5 ½-inch hole provides a small lip to generate downforce from the water head. • Compression Deflection = 2 to 5 psi. • Shore Durometer on 00 scale = 30 to 50. • Density = 7 to 11 pcf.	• Titanimum-based silicone caulk. Rubber-based silicone caulk was not recommended by John Mulke from HMA Lab Supply in Richmond, Virginia. • 3/8-inch thick bead applied on both sides of the rubber gasket around the circumference of the 5-1/2" hole. • Two 50-lb weights applied to base, water filled to top standpipe.

Figure 4.1 Applying Sealant to Rubber Gasket for Water Permeability Test

Figure 4.2 Filling NCAT Water Permeameter

Figure 4.3 Measuring Falling Head in NCAT Water Permeameter

4.2.2 Air Permeability Testing

The ROMUS air permeameter was used to collect data for a comparative analysis with the water permeameter on each project in the study. The ROMUS device is based on the falling-head air permeameter principle with one noted exception: a vacuum chamber is used to draw air through the pavement as opposed to a pressurized chamber forcing air into the pavement (Russell et al. 2004). While fundamentally consistent with air flow measures of earlier devices, the vacuum chamber also serves to enhance the seal between the device and the pavement surface. This is in contrast to a pressurized water permeameter chamber which must be ballasted to remain in contact with the pavement surface.

The main components of the ROMUS air permeameter include a hand-operated grease gun, base seal reservoir, vacuum chamber, automatic vacuum pump and valve, digital pressure gauge, and digital display. To initiate testing, the bottom of the ROMUS device is first sealed to the pavement surface by way of a grease seal. The sealant grease is manually pumped through the device into a recessed base ring which was sized to replicate the opening of the NCAT water permeameter. Manually pumping of the grease through the recess ring appears to provide an efficient seal that can easily conform to the surface irregularities present on asphalt pavements of the type investigated during this study. During field testing, the ROMUS permeameter could not achieve a good seal in the wheel paths if rutting exceeded approximately 1/8".

Once the device has been sealed to the pavement surface, pressing of the start button initiates a fully automated system that first creates a vacuum within the internal pressure chamber. When the vacuum pressure reaches a value of approximately 25 inches of water (47mm Hg), effectively simulating the maximum head of water used with the NCAT device, a valve automatically opens to allow air to be drawn through the pavement layer into the vacuum chamber. For this research project, the ROMUS device was programmed to record a single timing increment, to the nearest millisecond, representing a change in vacuum pressure equivalent to 8 inches of water. This set-up simulates a falling head water permeability test with a head drop from 20 – 12 inches of water. Once the test is complete, the timing increment is displayed on a digital display for manual recordation.

Air permeability testing was conducted using the ROMUS device at 20 test sites on each project, where 8 of 20 sites were comparative sites with the NCAT water permeameter. Air permeability testing was conducted after water permeability testing, with test locations offset 6 to 12 inches longitudinally to avoid the wet pavement surface. Figure 4.4 illustrates operation of the ROMUS device in this study.

Figure 4.4 Conducting Air Permeameter Test with ROMUS Device

4.3 Test Sites

A 0.1-mile segment was selected for each project, usually located 0.3 miles from the beginning of the selected Reference Point. The directional lane for testing corresponded with the PIF measurement lane. Within the 0.1-mile segment, 20 test sites were randomly chosen within each segment, and minor location adjustments were made to ensure adequate permeameter seating. The 20 test sites included air permeability and nuclear density testing, where 10 test sites were within the wheel path and 10 test sites were between the wheel paths. Tests in the wheel path assessed the relationship of permeability with rutting and densification from traffic. Tests between the wheel paths represented permeability and densification similar to as-built conditions.

Eight (8) of the 20 test sites were randomly selected for water permeability and core testing, where 4 sites were within the wheel path, and 4 sites between the wheel paths (see Figure 4.5 for schematic).

The base of the nuclear density gauge served as a reference point for water permeameter testing and coring. Cores were cut within the center of the base region. Surface fillers (sand, gels, water, etc.) were not be used. A six-inch diameter core was taken at the 8 test sites for the full depth of the asphalt pavement structure. Thickness of each pavement layer and the visual appearance were recorded. Cores were tested at the UW-Platteville Highway Technician Certification Program (HTCP) Lab. WisDOT Method 1559 (modified AASHTO T-166) was used to determine bulk density of core samples. The dry weight was recorded before submersion in the water bath; oven dryback to constant weight was not used since it would have reduced the integrity of the core sample for fatigue testing in Phase II of this study. JMF G_{mm} values were collected to determine core density as percentage of theoretical maximum density. It was not possible to collect location-specific Gmm values since the collected as-built data were incomplete.

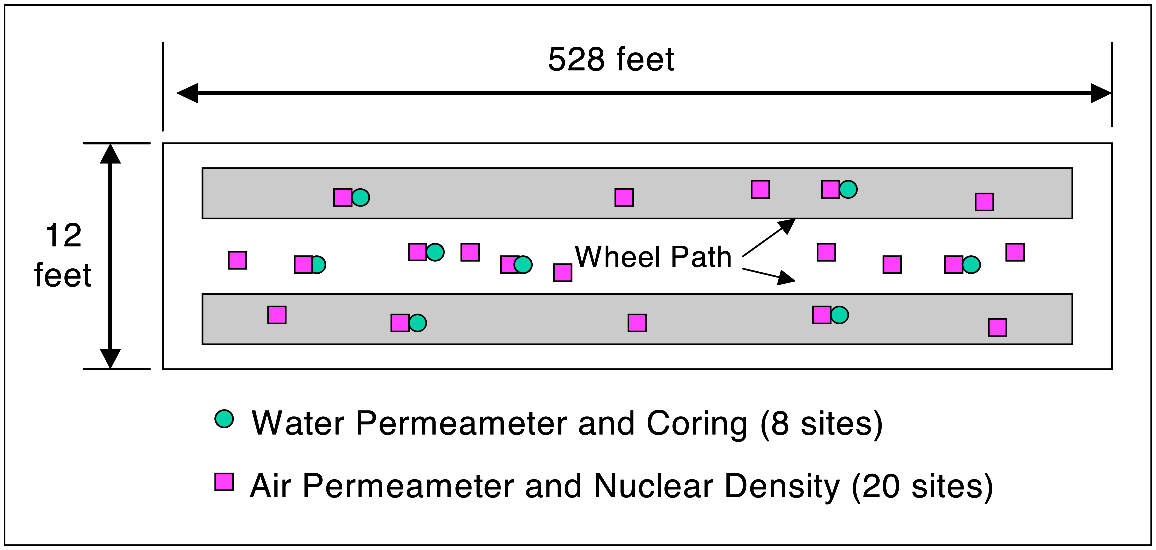

Figure 4.5 Test Site Schematic

CHAPTER 5 DATA COLLECTION SUMMARY

5.1 Projects

Field data were collected on 20 project segments between June 29 and July 25, 2006. Tables 5.1 through 5.7 summarize the data from each project; data are categorized by design, construction, traffic, and performance. There was difficulty collecting as-built construction data as noted by the blank cells; WisDOT Regions could either not locate the data or it was knowingly discarded 5 years after construction. In some cases, it was difficult to assign mix property test data to the specific 0.1-mile test segment, thus the cells were left blank to prevent any incorrect entries.

Table 5.2 presents aggregate gradation data from the JMF, with the exception of Projects #13 and #18 (STH 23 and USH 8) where the specific construction test data were entered from the 2004 WHRP permeability-density study. All projects were fine-graded mixes, as measured by the percent passing 4.75mm sieve, where all percentages were above the 45% value defining a fine-graded mixture according to WisDOT. Aside from Stone Matrix Asphalt (SMA) projects, it was not possible to identify coarse-graded mixtures from a comprehensive database. From the 2004 study, research notes indicated that very few coarse-graded Superpave projects had been constructed, and when a coarse-graded mix was paved, it was typically a lower layer with a fine-graded mixture paved on the surface layer.

Tables 5.3 and 5.4 report mix properties from the JMF, again with the exception of Projects #13 and #18 (STH 23 and USH 8) where the specific as-built mix property test data were known. Table 5.5 provides density data and research project averages for water permeability, air permeability, and core thicknesses. As-built pavement density data were received from only 9 of the 20 projects, as shown in Column 3 of this table. A majority of these missing cells are from projects paved in 2000. Projects where as-built density data were collected ranged from 1995, 2000, 2002 to 2003. Performance data from research field distress surveys on each of the 20 projects are provided in Tables 5.6 and 5.7.

Table 5.1 DESIGN – Project Number and Base Type

Project	Hwy	County	Age, years	New Pavt. Thick., in.	Base Type	Mill Depth, in.	ESALs (MV=3)
1	59	GREEN	11	4.5	Old AC	0	3
2	11	ROCK	11	4.5	Old AC	0	10
3	60	SAUK	8	4.50	Old AC	0	3
4	14	RICHLAND	6	3	Rubblize	0	3
5	60	CRAWFORD	8	3.00	Pulverize	0	3
6	129	GRANT	6	4.5	Pulverize	7	3
7	58	JUNEAU	6	1.5	Old AC	0	3
8	131	MONROE	6	5	DGBC	4.75	10
9	12	EAUCLAIRE	6	4.5	Full Depth Mill	6	3
10	64	CHIPPEWA	6	4.5	Pulverize	4	3
11	77	WASHBURN	6	4.5	Old AC	0	3
12	13	DOUGLAS	6	4	Pulverize	0	3
13	23	MARQUETTE	4	4.25	Existing AC	1.2	3
14	96	WAUPACA	4	4	Old AC	0	10
15	22	WAUPACA	6	4	Pulverize	0	3
16	96	BROWN	6	3.5	Old AC	0	3
17	47	VILAS	3	3.5	Pulverize	0	1
18	8	ONEIDA	3	6	CABC	0	3
19	32	FOREST	3	4.5	Pulverize	5	3
20	70	FOREST	3	3.5	Old AC	0	1

Table 5.2 CONSTRUCTION - Percent Passing Sieves from Job Mix Formula

Project	19mm	12.5mm	9.5mm	4.75mm	2.36mm	1.18mm	0.60mm	0.30mm	0.15mm	0.075mm
1	98.5	92.9	84.3	60.3	51.3	.	34.2	10.8	.	5.4
2	100	97.9	92.3	71.6	51.9	37.1	25.8	15.1	8.7	5.9
3	100	96.0	87.8	66.6	54.4	46.6	37.8	17.0	6.7	4.4
4	100	95.1	79.7	62.2	49.1	42.1	33.8	14.7	5.6	3.7
5	100	97.2	88.6	67.5	52.0	39.3	29.2	16.0	8.6	4.9
6	100	94.9	88.9	71.6	54.0	43.1	31.2	17.5	8.7	5.3
7	100	98.0	94.1	72.0	56.9	47.6	40.3	21.3	9.4	6.0
8	100	94.8	87.8	64.7	45.3	34.8	25.3	12.5	6.0	4.2
9	100	92.0	77.6	60.6	50.2	45.1	38.9	23.7	6.6	4.2
10	100	93.9	85.3	64.5	50.2	32.3	22.5	10.5	5.4	3.8
11	100	93.2	78.8	56.3	44.0	32.8	20.6	9.5	6.2	4.4
12	100	92.5	79.2	57.0	47.2	41.3	34.5	20.1	7.3	3.6
13	100	97.0	85.7	68.7	52.5	40.7	32.4	16.3	7.6	4.5
14	100	97.4	88.3	69.4	49.6	37.3	28.3	14.8	5.9	3.7
15	100	94.7	85.4	69.7	54.5	45.4	36.4	19.7	7.6	4.2
16	100	96.5	86.1	66.2	51.4	38.6	29.2	15.5	6.2	4.1
17	100	96.6	87.6	66.5	51.5	40.0	28.5	14.2	7.2	4.9
18	100	96.1	85.3	60.2	47.0	36.4	26.2	11.0	5.2	3.3
19	100	93.1	83.2	68.6	58.6	49.2	39.6	20.5	8.7	5.7
20	100	94.6	83.8	64.8	55.7	48.9	35.9	12.2	6.1	4.5

Table 5.3 CONSTRUCTION – Aggregate Properties from Job Mix Formula

Project	Mfg. Sand Percentage	Crushed Faces 1	Crushed Faces 2	F.A.A.	S.E.	Gsb	Gse	Moist. Absorb.	Sound-ness	L.A. Wear	Freeze-Thaw	Elong-ated
1	0	96.8	.	.	.	2.635	2.673	.	.	10.9	.	1.7
2	46	.	.	.	.	2.670	2.737	0.9	.	.	.	.
3	0	89.5	.	.	.	2.669	2.691	.	.	.	.	4.8
4	32	99.8	99.8	.	.	2.672	2.695	0.3	.	.	.	1.5
5	20	98.3	.	.	.	2.704	2.727	.	.	.	.	0.3
6	15	98.2	98.4	.	.	2.684	2.741	0.8	.	.	.	1.5
7	0	69.2	.	.	.	2.700	2.745	.	.	.	.	4.3
8	25	.	.	.	.	2.657	2.728	0.9	.	.	.	.
9	50	100.0	100.0	.	.	2.570	2.608	0.6	.	.	.	3.8
10	35	68.8	64.8	.	.	2.688	2.725	0.5	.	.	.	2.4
11	25	85.0	.	.	.	2.675	2.726	.	.	.	.	2.1
12	0	97.6	97.3	.	.	2.782	2.806	0.3	.	.	.	3.5
13	25	89.4	87.5	43.2	76.0	2.682	2.763	1.3	1.2	7.8	1.7	1.5
14	41	90.3	90.2	44.7	89.2	2.716	2.762	.	0.9	4.4	.	2.6
15	40	97.1	95.0	.	.	2.695	2.725	.	2.7	23	.	2.7
16	24	95.0	0.0	.	.	2.709	2.762	.	.	.	.	0
17	54	91.0	86.0	43.9	73.0	2.687	2.735	.	2.4	4.6	.	1
18	25	100.0	100.0	44.2	79.0	2.663	2.701	0.7	2.2	3.7	0	2
19	50	76.2	64.6	42.3	78.0	2.675	2.705	0.6	0.1	19.7	.	2.1
20	0	71.3	3.2	.	.	2.655	2.708	.	.	.	.	.

Table 5.4 CONSTRUCTION – Mixture Volumetrics from Job Mix Formula

Project	Ndes	Gmb	Gmm	Voids	VMA	VFB	AC	TSR	Dust Prop.
1	50	2.378	2.475	3.6	14.0	.	5.0	86.0	.
2	75	2.408	2.496	3.5	15.1	76.0	5.8	83.9	1.0
3	50	2.373	2.460	3.5	16.2	.	5.8	71.0	.
4	50	2.373	2.457	3.4	16.5	.	6.0	70.2	0.8
5	50	2.384	2.470	3.5	17.4	.	6.3	85.0	.
6	50	2.398	2.485	3.5	16.2	77.6	6.2	71.1	1.0
7	50	2.427	2.517	3.6	15.0	76.2	5.5	80.6	.
8	100	2.419	2.520	4.0	13.5	70.4	5.0	85.7	1.0
9	50	2.282	2.365	3.5	17.1	.	6.7	96.8	0.7
10	50	2.385	2.472	3.5	16.7	.	6.2	73.3	0.7
11	50	2.409	2.499	3.5	14.5	.	5.6	87.0	.
12	50	2.450	2.538	3.5	17.3	80.0	6.1	99.7	.
13	75	2.432	2.524	3.6	14.3	74.8	5.4	77.8	0.9
14	100	2.454	2.556	4.0	14.0	71.4	4.8	77.2	0.9
15	50	2.416	2.503	3.5	15.2	77.2	5.4	71.5	0.8
16	50	2.435	2.524	3.5	15.1	76.7	5.6	86.2	.
17	60	2.416	2.517	4.0	14.7	72.8	5.2	80.0	1.1
18	75	2.383	2.485	4.1	15.1	72.8	5.1	72.5	0.8
19	60	2.382	2.482	4.0	15.8	74.7	5.1	78.9	1.3
20	60	2.358	2.457	4.0	16.7	76.0	6.2	91.3	0.8

Table 5.5 CONSTRUCTION AND IN-SERVICE – Density and Permeability

Project	Density Required %	Density time=0 %	Density time=age %	Water Perm. time=age 10E-5 cm/s	Air Perm time=age 10E-5 cm/s	Top Layer Thickness inches
1	92.0	.	96.4	0.2	2.3	1.5
2	92.0	92.0	96.4	0.3	1.2	1.4
3	.	.	97.5	0.5	4.4	1.3
4	.	.	97.0	0.3	2.7	1.2
5	.	.	94.5	2.0	14.1	1.6
6	.	.	96.1	0.4	8.0	1.5
7	.	.	96.3	0.4	6.2	1.5
8	.	.	93.1	1.8	15.7	1.4
9	91.0	92.1	97.7	1.7	7.2	1.8
10	.	.	97.7	3.9	4.4	.
11	91.0	.	96.5	0.6	11.3	1.5
12	91.0	.	96.7	0.2	5.3	1.5
13	91.5	92.7	95.6	0.3	5.4	1.6
14	92.0	91.6	93.5	0.4	6.5	1.6
15	91.0	94.8	95.8	0.1	11.8	1.6
16	.	.	95.6	0.1	5.6	1.6
17	91.5	91.9	94.2	0.1	10.3	1.5
18	91.5	92.6	97.7	0.1	4.3	1.1
19	91.5	92.4	96.1	0.0	18.9	1.9
20	91.5	93.8	96.6	0.1	7.7	1.3

Table 5.6 PERFORMANCE – Cracking and Edge Raveling

Project	Block Cracking, % area	Block Cracking, Severity	Trans. Cracking, No./528 ft.	Trans. Cracking Severity	Long. Cracking L.F./528 ft.	Long. Cracking Severity	Edge Raveling Severity	Crack Filliing
1	24	1	13	1	100	1	0	1
2	0	0	6	1	0	0	0	1
3	0	0	0	0	0	0	0	2
4	0	0	0	0	100	1	0	2
5	0	0	0	0	0	0	0	2
6	0	0	0	0	100	1	0	2
7	74	1	23	1	205	1	1	1
8	0	0	0	0	100	1	0	2
9	0	0	12	3	100	1	0	2
10	0	0	5	1	100	1	0	2
11	0	0	10	2	100	1	0	2
12	0	0	6	2	0	0	0	1
13	0	0	13	2	0	0	0	0
14	0	0	10	2	85	1	1	2
15	0	0	0	0	5	1	0	2
16	0	0	6	1	100	1	1	2
17	0	0	6	1	0	0	0	2
18	0	0	0	0	0	0	0	2
19	0	0	0	0	0	0	0	2
20	0	0	8	3	0	0	1	2

Table 5.7 PERFORMANCE – Cracking and Edge Raveling

Project	PDI (WisDOT)	IRI, (WisDOT) m / km	PSI (WisDOT)	Rut (WisDOT) inches	Rut Left Wheel Path (study) Inches	Rut Right Wheel Path (study) inches	Average Rut (study) inches
1	64	1.77	3.1	0.22	0.16	0.16	0.16
2	14	1.03	4.5	0.08	0.07	0.00	0.04
3	10	1.23	4.2	0.21	0.31	0.27	0.29
4	9	0.88	4.7	0.09	0.13	0.10	0.11
5	8	1.34	3.9	0.09	0.25	0.20	0.22
6	18	1.24	4.1	0.28	0.09	0.27	0.18
7	50	1.47	3.6	0.10	0.07	0.14	0.10
8	15	0.82	4.8	0.08	0.03	0.10	0.07
9	38	1.35	3.9	0.14	0.13	0.19	0.16
10	8	0.98	4.7	0.10	0.11	0.16	0.14
11	18	1.03	4.6	0.21	0.08	0.21	0.15
12	8	1.57	3.4	0.11	0.08	0.10	0.09
13	11	0.79	4.9	0.04	0.00	0.05	0.03
14	25	0.83	4.9	0.04	0.03	0.05	0.04
15	4	1.12	4.3	0.07	0.09	0.10	0.10
16	26	0.93	4.6	0.06	0.13	0.07	0.10
17	29	1.08	4.4	0.10	0.10	0.15	0.13
18	11	0.79	4.9	0.06	0.13	0.06	0.09
19	4	0.78	4.9	0.07	0.17	0.07	0.12
20	4	0.93	4.7	0.13	0.19	0.14	0.16

5.2 Comparison of Cores and Nuclear Density Gauge

Table 5.8 provides a comparison of core densities with the research nuclear density gauge readings (CPN Model MC-3, Serial #M391105379). Cores were tested at the UW-Platteville HTCP lab using WisDOT Method 1559 (modified AASHTO T166). Initially, 8 cores were sampled on the first set of projects, however, the abrasive and highly-densified in-service pavements caused significant wear to the core bits and unexpected costs, thus the number of cores was reduced to 2 on the final projects. The reason for this smaller number was to ensure the layer thickness for permeability calculations, and to provide an offset value to adjust the nuclear density readings.

Table 5.8 Core and Nuclear Gauge Comparison

Project Index (1)	Roadway Name (2)	Comparison Sites, n (3)	Nuclear Gauge, pcf (4)	Core pcf (5)	Mean Diff., pcf (6)	Std. Deviation, of Diff., pcf (7)
1	STH 59	8	147.0	148.5	-1.5	1.06
2	STH 11	8	149.6	149.8	-0.2	0.88
3	STH 60 Sauk	8	147.9	149.4	-1.5	1.82
4	USH 14	2	149.4	148.0	1.4	0.11
5	STH 60 Crawford	8	145.2	145.3	-0.1	0.91
6	STH 129	8	149.7	148.7	1.0	1.31
7	STH 58	8	149.2	150.6	-1.4	0.83
8	STH 131	8	144.3	146.0	-1.8	0.66
9	USH 12	5	141.7	143.6	-1.9	1.61
10	STH 64	0	n/a	n/a	n/a	n/a
11	STH 77	2	149.1	149.7	-0.6	2.08
12	STH 13	2	154.7	151.7	3.0	0.99
13	STH 23	2	151.3	149.6	1.6	0.08
14	STH 96 Waupaca	2	152.2	150.1	2.1	0.32
15	STH 22	2	148.6	149.1	-0.5	0.99
16	STH 96 Brown	2	150.0	149.6	0.4	0.01
17	STH 47	2	146.3	146.6	-0.3	0.23
18	USH 8	2	147.7	149.5	-1.8	0.31
19	STH 32	2	148.8	148.0	0.7	0.78
20	STH 70	2	150.5	148.1	2.4	0.65

Relative to cores, the nuclear gauge read lower on 11 projects ranging from 0.1 pcf to 1.9 pcf, and higher on 8 projects ranging from 0.4 pcf to 3.0 pcf. These offset values adjusted the nuclear gauge reading to the core density for the data analysis. For example, on the STH 13 project all raw nuclear gauge readings were reduced by 3.0 pcf to reflect the difference with the average core density.

5.3 Comparison of Permeability Measurement Methods

The ROMUS device was used in tandem with the NCAT device at 8 test sites per project, yielding 160 possible test sites. During field testing, it was not possible to conduct a valid air permeameter test at each comparison site because of wheel ruts, rough surface texture, or an impermeable surface. Figure 5.1 provides an aggregate comparison of equivalent water permeabilities measured by the ROMUS device versus NCAT device by individual test site. The data were stratified by 3 transverse locations in the driving lane, including the left wheel path, right wheel path, and between the wheel paths.

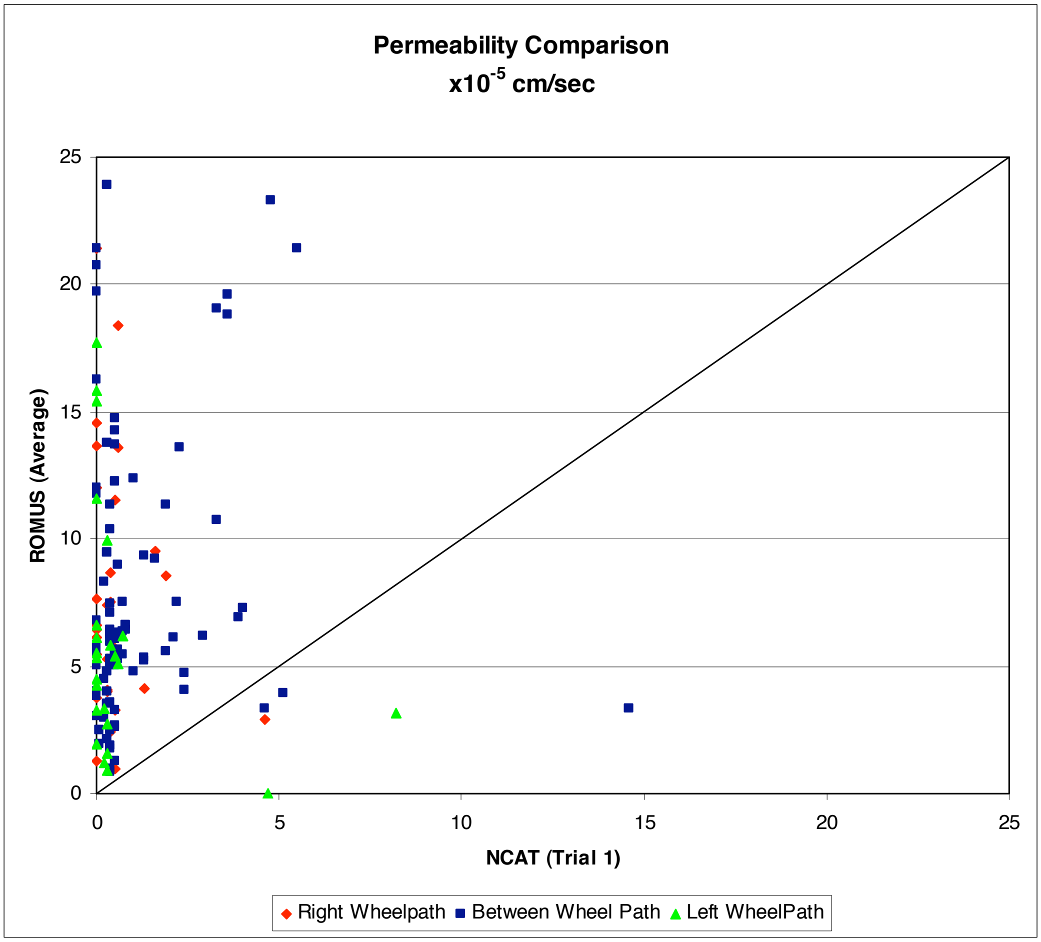

Figure 5.1 Comparison of Permeability Methods and Wheelpath Location

From Figure 5.1, air and water permeability was very low, not exceeding 25 x 10E-5 cm/sec with the air permeameter and 15 x 10E-5 cm/sec with the water permeameter. Except for 2 out of 160 test sites, water permeability values were less than 5 x 10E-5 cm/sec, thus the pavements were nearly impermeable. Air permeameter values had a higher order of magnitude than the water permeameter with a majority of points above the line-of-equality. Also, water permeability values between wheel paths were generally higher than in the wheel paths.

A polynomial least-squares regression line was fitted with the air and water permeability data and is shown in Figure 5.2. Similar to the 2002 WHRP permeability-density study, the rate of pavement permeability with the ROMUS device was generally a factor of 10 greater than the NCAT device. Tests measuring a zero permeability value with the NCAT device yielded values from 1 to 22 x 10E-5 cm/sec with the ROMUS device. Although the regression line indicated an upward trend, there was significant amount of scatter as denoted by the R-squared = 6.5%, and a reasonable model using other fitting techniques having a substantial R-squared could not be constructed.

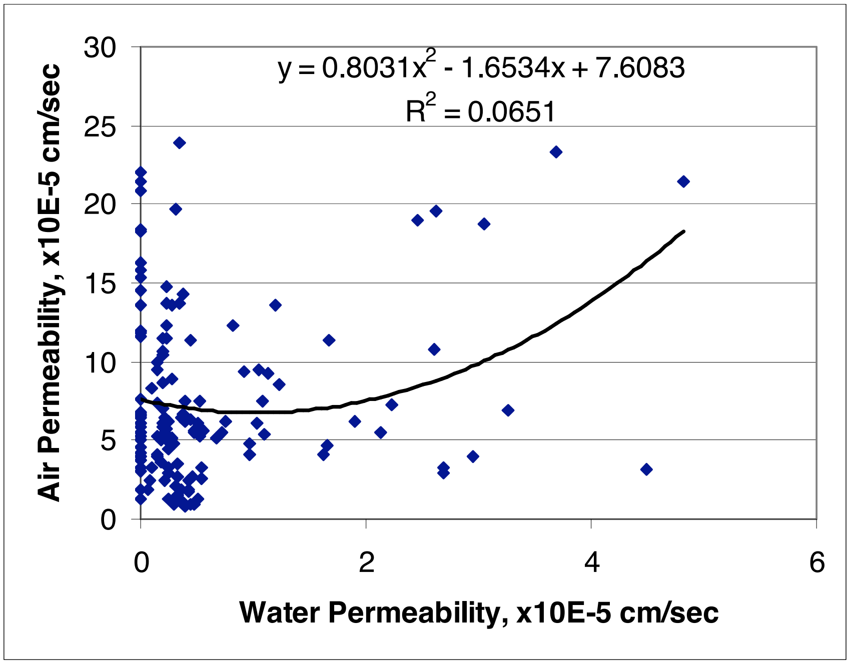

Figure 5.2 Comparison of Permeability Methods and Wheelpath Location

Permeability results were plotted against the in-service pavement density, as shown in Figure 5.3 and 5.4, respectively. As shown in Figure 5.3, the pavement was nearly impermeable with water permeability values less than 5 x 10E-5 cm/sec, and no trend was observed between permeability and density. By comparison, the 2002 WHRP permeability-density study found that no trend existed for fine-graded gravel-source mixes, but a trend was observed for fine-graded limestone-sourced mixes (Russell et al. 2004). Also by comparison, NCHRP 9-27, a comprehensive density-permeability study that evaluated 37 mixtures, found that variability of permeability among mixtures was very high with some more permeable at 90 to 92% density and others not (Brown et al. 2004). Both studies concluded that the permeability-density relationship is mixture specific with respect to as-constructed pavement density, say in the range of 90% to 93%, while this study measured higher-density pavements that had been exposed to years of vehicle traffic. The insignificant linear regression equation in Figure 5.3 further supports that there is no relationship between water permeability and in-service pavement density for values ranging from 92% to 99%. In Figure 5.4, air permeability trended downward with an increase in density, while water permeability had no discernible trend.

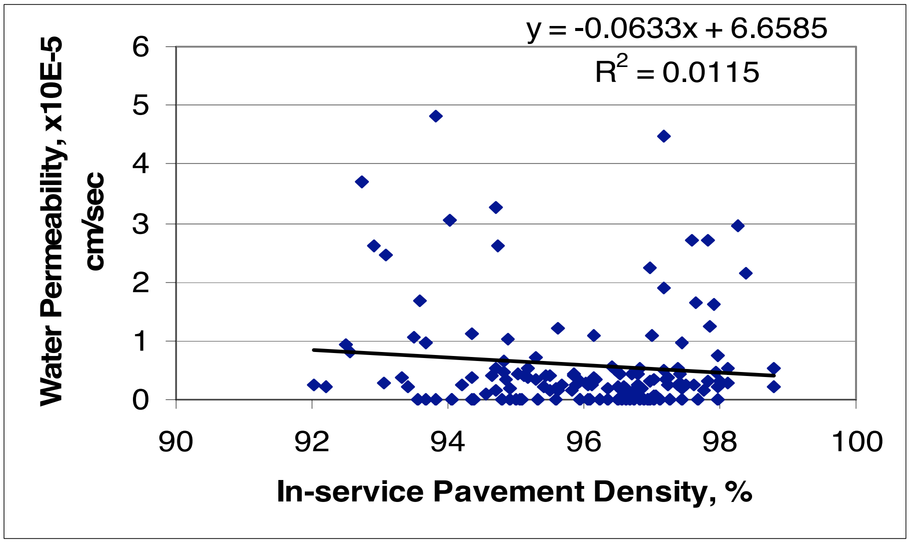

Figure 5.3 Relationship of Water Permeability and In-Service Pavement Density

Air permeability results were plotted against in-service pavement density, and fitted with a linear regression line, as shown in Figure 5.4. The regression model R-squared = 16% supports a downward trend where an increase in density yielded lower air permeability values. This finding agrees with the 2002 WHRP study where pavement density had an effect on air permeability, in the range of 90% to 93% density (Russell et al. 2004). The totality of Figures 5.1 through 5.4 highlights differences between the ROMUS and NCAT devices for measuring pavement permeability, and their relationship with pavement density for values above 92% density.

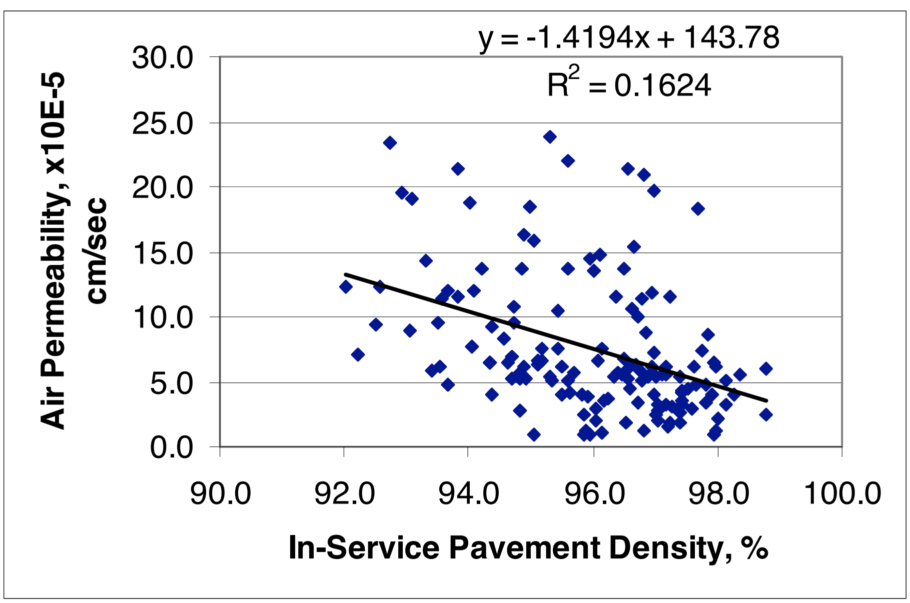

Figure 5.4 Relationship of Air Permeability and In-Service Pavement Density

The collected field data were summarized for the relationship between pavement surface layer thickness and both pavement density and permeability results. Figure 5.5 plotted surface layer thickness with in-service pavement density, and no trend was observed. As the layer thickness increased, the in-service density slightly decreased. Each thickness increment had scatter in pavement density.

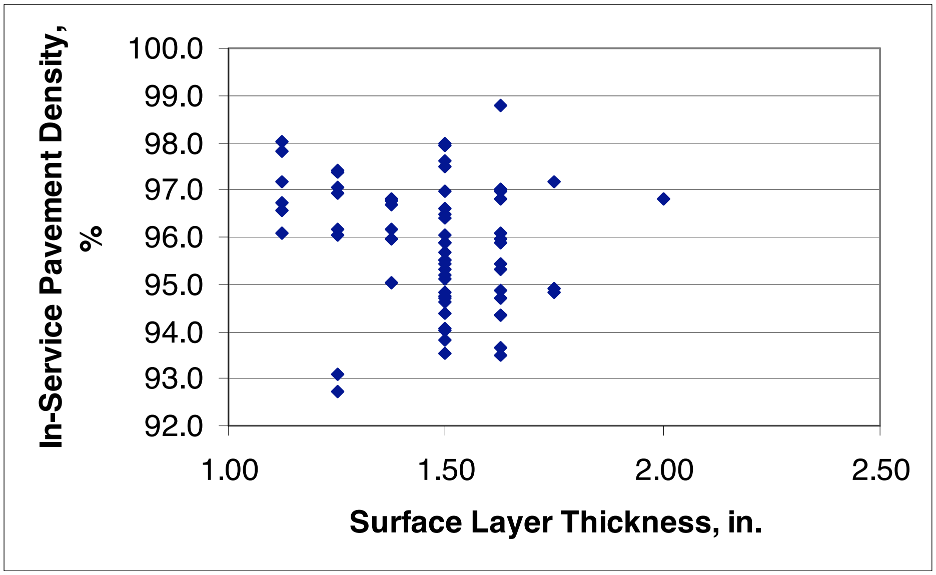

Figure 5.5 Relationship of Surface Layer Thickness and In-Service Pavement Density

Figures 5.6 and 5.7, respectively, plotted water and air permeability with surface layer thickness. In both cases, there was no clear relationship between permeability and layer thickness. This supports a finding from the 2004 WHRP study where layer thickness and the thickness-to-NMAS ratio did not have a clear relationship with permeability in fine-graded mixes (Russell et al. 2004). In this study, higher density values were measured, and the same conclusion was reached.

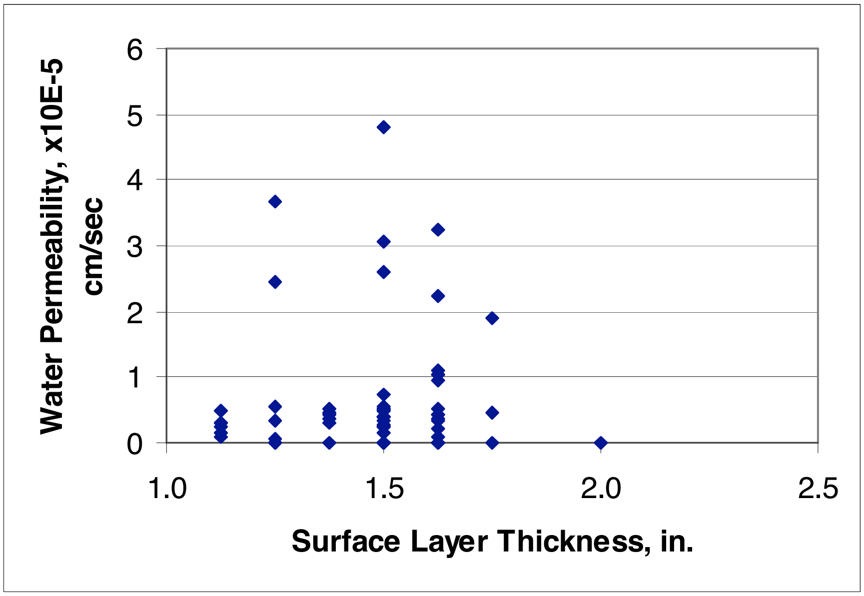

Figure 5.6 Water Permeability and Surface Layer Thickness

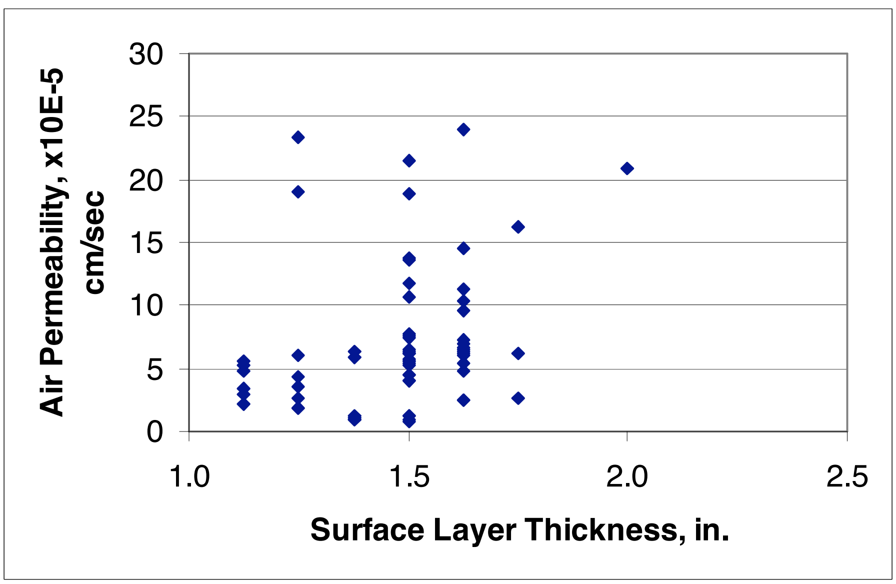

Figure 5.7 Air Permeability and Surface Layer Thickness

5.4 Summary

In this chapter, collected data in the study were summarized by design, construction, traffic, and performance categories (20 projects). Data were also summarized from the individual test site data, including both water and air permeability, in-service pavement density, and surface layer thickness (400 test sites; 20 projects at 20 sites per project).

Air and water permeability was very low, not exceeding 25 x 10E-5 cm/sec with the air permeameter and 15 x 10E-5 cm/sec with the water permeameter. Except for 2 out of 160 test sites, water permeability values were less than 5 x 10E-5 cm/sec, thus the pavements were nearly impermeable.

Air permeability with the ROMUS device was a factor of 10 greater than the NCAT device. Water permeability values between wheel paths were generally higher than in the wheel paths. Air permeability trended downward with an increase in density, while water permeability had no discernible trend coupled with an insignificant linear relationship.

When surface layer thickness was compared to in-service pavement density, no trend was observed. As the layer thickness increased, the in-service density slightly decreased. There was no clear relationship between permeability and surface layer thickness.

In the next chapter, a detailed analysis is presented with emphasis on the NCAT water permeameter since this device had been used in previous studies as the baseline measure for pavement permeability. Performance measures, project, and mixture-specific relationships are investigated.

CHAPTER 6 DATA ANALYSIS

6.1 Introduction

This chapter presents the analysis to address a key study objective: to understand the inter-relations of HMA mixture properties, in-place permeability, density, and pavement performance. Data presented in the previous chapter were used in this analysis, thus, the sample size was generally n=20, except for columns having missing cells. Test results with the NCAT device were used as the primary measure for pavement permeability. Then, using conclusions from the analysis, the following chapter addresses the second key objective, establishing target permeability and density values suitable for use within contract specifications.

6.2 Correlation Results

Simple correlations were computed for every combination of variables presented in Tables 5.1 through 5.7, including the design, construction, traffic, and performance categories. Correlation is a measure of the degree of linear relationship between two independent variables. Although a non-linear relationship may exist between any two variables, simple correlation can detect a positive or negative trend for smaller sample sizes. In this application, the Pearson correlation coefficient was computed, along with probability of significance between the two variables (0.10 or less indicating significant). A restriction of using this method was that it could not measure collinearity among more than two independent variables. The reason for using this method was to perform an initial screening of variables having a significant relationship, then to conduct a more detailed investigation using other methods.

Due to the relatively small sample size (n=20), it was not possible to perform a full multiple regression using traditional forward or backward selection techniques. The number of independent variables (n=57) is greater than the sample size, thus there were insufficient degrees of freedom to perform a valid model construction.

Table 6.1 summarizes significant correlations between any two variables warranting further analysis. In several cases, two variables were related, however, the relationship lacked practicality and was not investigated further. For example, IRI and aggregate bulk specific gravity (Gsb) were related, however, their relationship has little practical importance for specifications.

Table 6.1 Significant Correlations between Two Independent Variables

Variable 1	Variable 2	Commentary
Rut Depth (as measured by WisDOT performance van)	Milling Depth IRI VMA Ndes Asphalt Content	
PDI	Age	
Block Cracking Extent	Structural Thickness	• 2 of 20 segments had block cracking
Edge Raveling	AATT	
Air Permeability	Age AATT 75um sieve Manufactured Sand % blend Air Voids (design) VMA (design) Rut Depth (average of both paths) Transverse Cracking Severity Density at current age Layer Thickness	• Mix property data are from Job Mix Formula, and do not represent actual field values within the 0.1-mile test segment.
Water Permeability	AADT AATT 75um sieve Manufactured Sand % blend FAA Air Voids (design) VMA Ndes Density at construction Rut Depth (average both paths) Transverse Cracking Severity Edge Raveling Density at current age Layer Thickness	• 5 of 20 projects had FAA data. • Mix property data are from Job Mix Formula, and do not represent actual field values within the 0.1-mile test segment.

6.3 Analysis of a Performance Measures

In this section, pavement performance measures were plotted against permeability and density to investigate their relationship. Several individual distresses and the composite PDI value were used as measures of performance in the analysis. A result of using the PDI is the inability to understand which individual distresses have the greatest contribution, or relative weight, to the PDI score. Thus, a graphical analysis was conducted to understand the relationship between the PDI value, individual distresses, and both permeability and density. The analysis also evaluated two density measures: (1)

as-built density from construction, and (2) in-service density from July 2006. A weakness of analyzing the as-built density was a sample size of n=9, since it was only possible to collect data from 9 of 20 projects.

6.3.1 Performance and Density

A minimum as-constructed pavement density of 92% is considered by most state highway agencies to provide a long-lasting, durable asphalt pavement (Roberts et al. 1996). Studies have proven that over-compacting the pavement, say to 96% or higher, may have an adverse affect on performance. As a result, both as-built and in-service density were investigated with respect to the PDI and individual distress measures measured on the projects.

Figures 6.1 and 6.2 plot the PDI against as-built density and in-place density, respectively. Figure 6.1 has 9 data points since as-built density were available for 9 of 20 projects, while it was able to collect all project data (n=20) for Figure 6.2. In Figure 6.1, pavements having a lower as-built density performed at a lower level (higher PDI value). The three data points with PDI values at or above 25 had ages of 3, 4, and 6, while the lesser PDI values ranged from 3 to 11 years in age. Therefore, when all other variables are removed from consideration, including age, as-built pavement density appears to have an effect on performance. This relationship is further investigated in a following section. Figure 6.2 illustrates that no clear trend was observed for PDI and in-service density, despite two data points having large PDI values at about 96% density.

An important feature of Figure 6.2 was that in-service densities were generally dispersed around a median of 96% density, indicating that an appropriate Ndes level is being used during the mixture design process. It is recommended that further monitoring be conducted to verify that Ndes values correlate with in-service density.

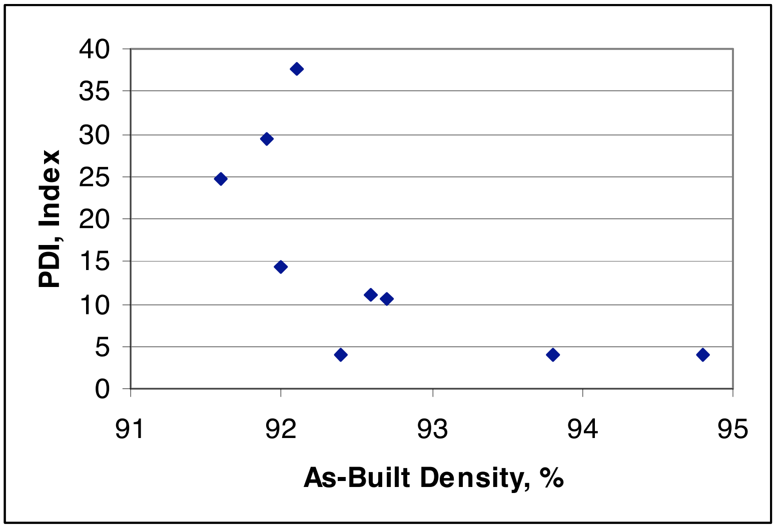

Figure 6.1 As-Built Density and PDI

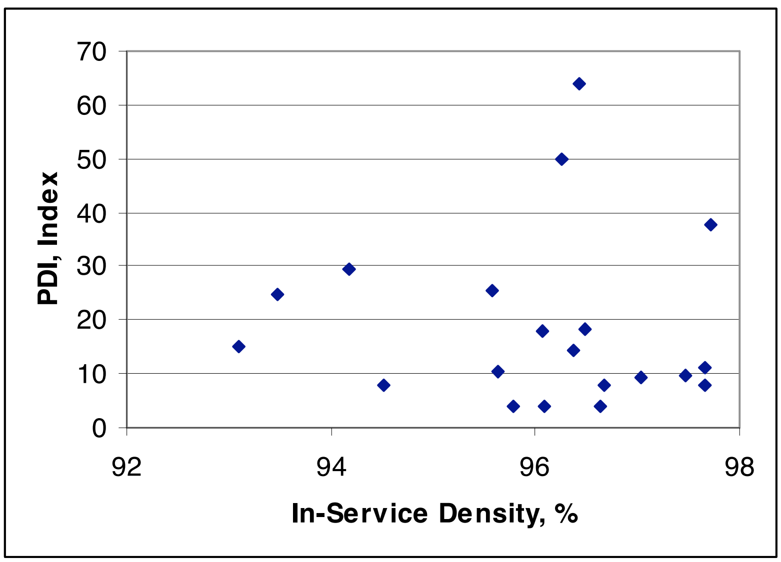

Figure 6.2 In-Service Density and PDI

To gain an understanding of densification of pavements with time and traffic, as-built density was plotted against in-service density in Figure 6.3. Only 9 data points were used since as-built density data was provided for 9 of 20 projects. This figure shows that density generally increased 2 to 5% between as-built and in-service periods. Figure 6.4 plots age and PDI, where there was no definitive trend, with the exception of the large PDI at 11 years of age with the STH 59 project (paired with lower PDI, STH 11 project). The experimental design purposely selected lower and higher performing pavements for a same age and traffic level, so the result in Figure 6.4 was expected.

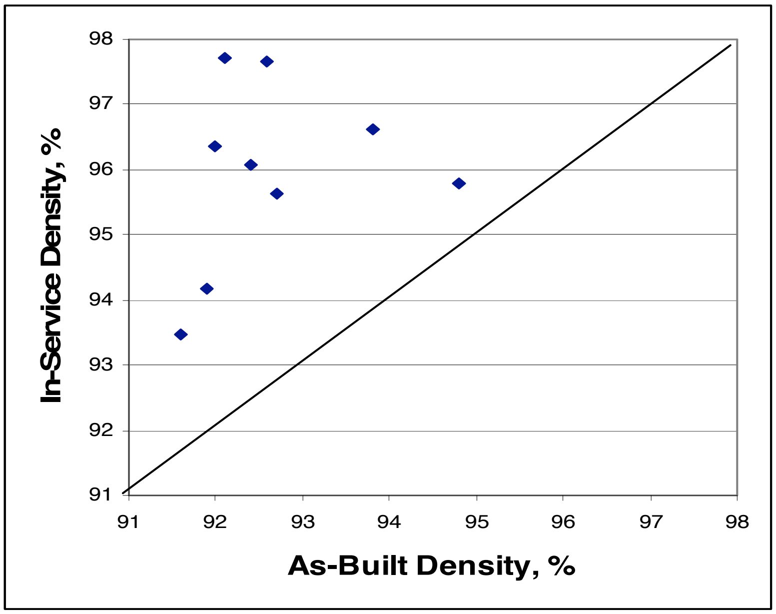

Figure 6.3 Comparison of As-Built and In-Service Density from 9 Projects

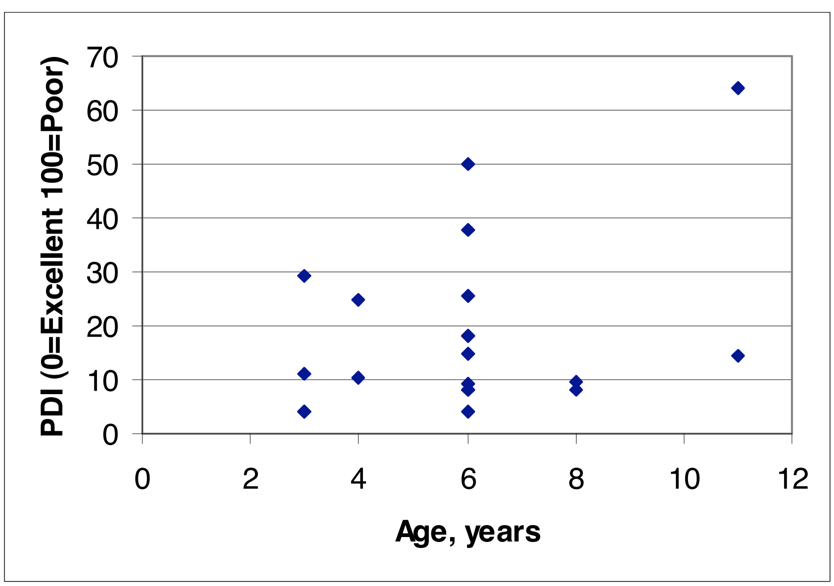

Figure 6.4 Relationship of Age and PDI

Figure 6.5 and 6.6 relate rut depth with density. Both plots had random scatter and no definitive trend.

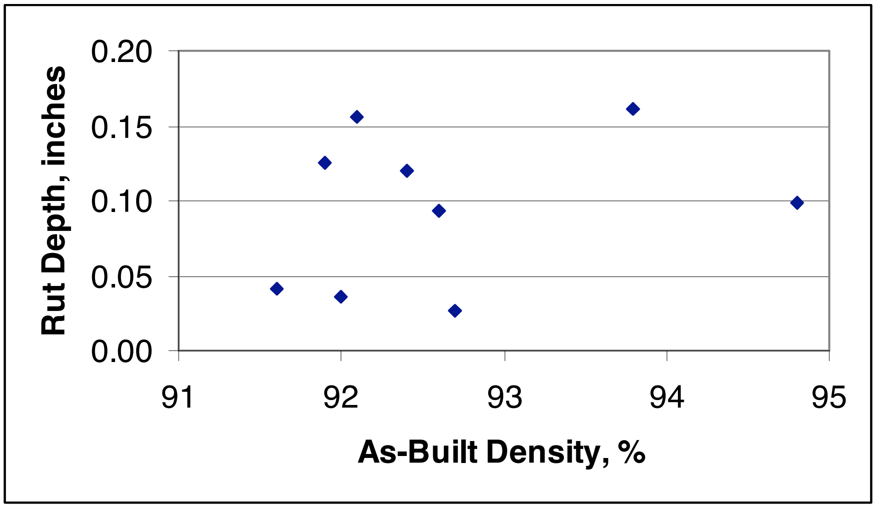

Figure 6.5 As-Built Density and Average Rut Depth

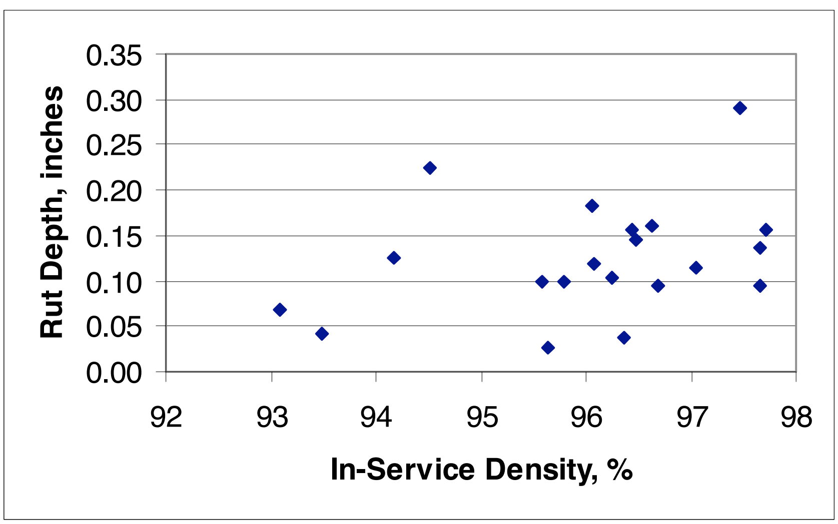

Figure 6.6 In-Service Density and Average Rut Depth

Rut depth data were stratified by wheel path location (left and right) to assess any potential effect (see Figures 6.7 and 6.8). From this stratification, no clear delineation between wheel path location and density could be found.

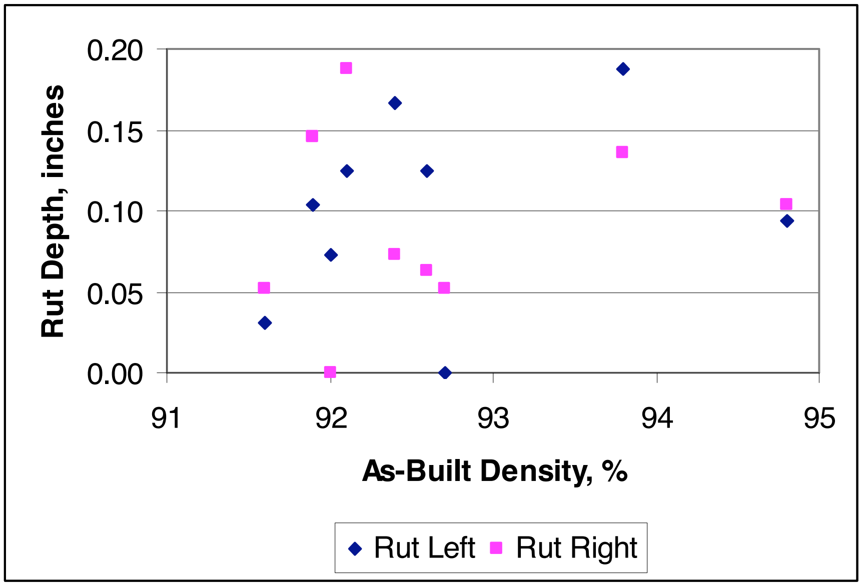

Figure 6.7 As-Built Density and Rut Depth by Wheel Path

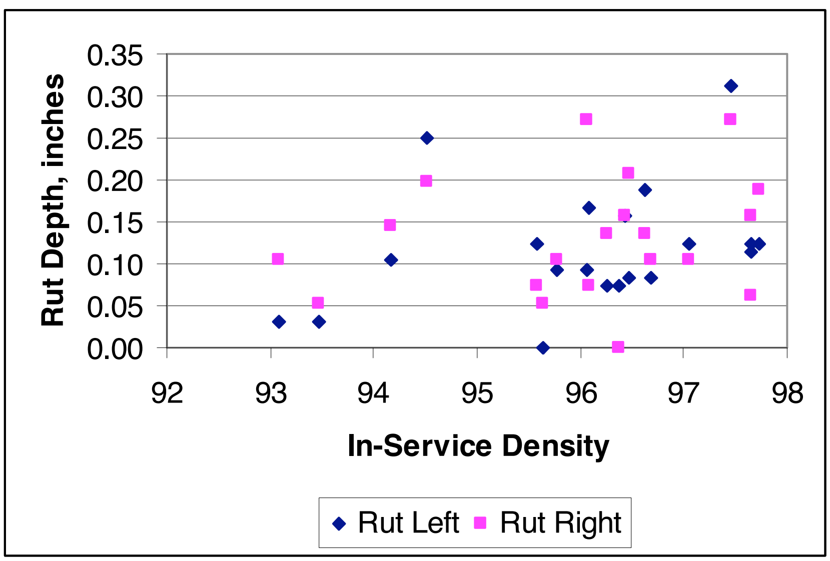

Figure 6.8 In-Service Density and Rut Depth by Wheel Path

Transverse cracking was observed on several projects, and the extent (number of cracks per 528-foot test section length) was plotted against density (Figures 6.9 and 6.10). A slight positive trend was observed for in-service density, while as-built density may have had an influence but there were limited data points. It appeared that lower as-built density may cause a greater frequency in cracking.

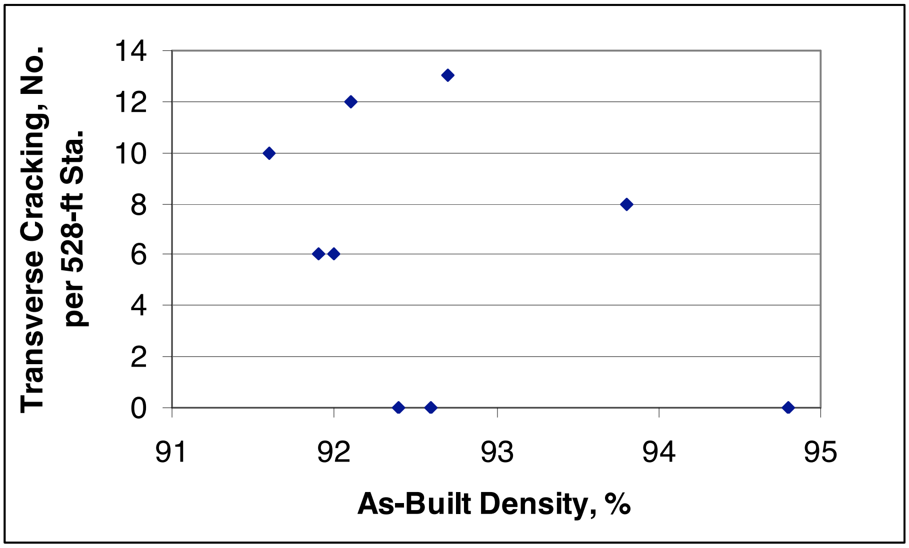

Figure 6.9 As-Built Density and Transverse Cracking Extent

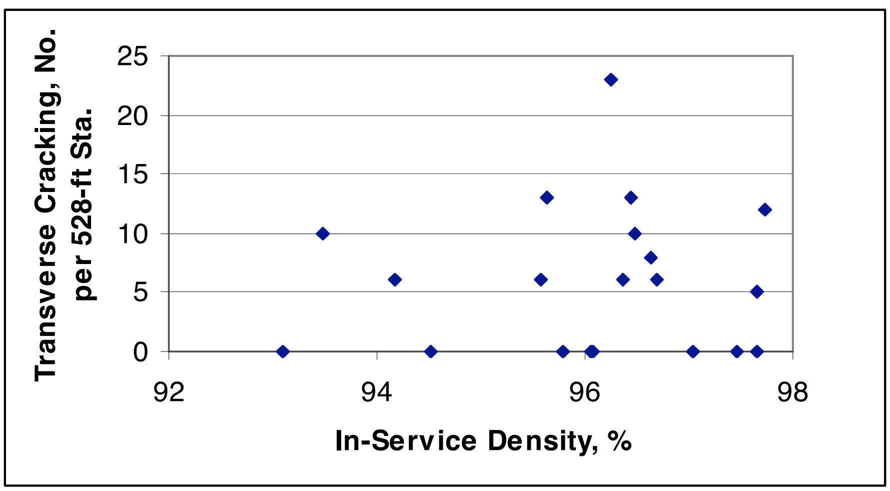

Figure 6.10 In-Service Density and Transverse Cracking Extent

Nearly all longitudinal cracking was measured in either the right or left wheel path. Longitudinal cracking extent (L.F. per 528-foot test section length) was compared with density, as shown in Figures 6.11 through 6.12. There appeared to be greater extent of cracking for as-built densities lower than 92%, and no relationship was observed across a wide range of in-service densities.

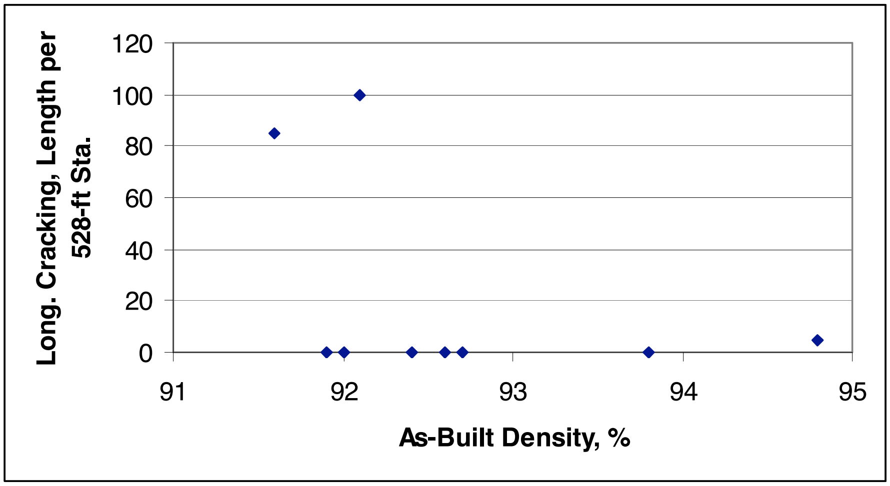

Figure 6.11 As-Built Density and Longitudinal Cracking Extent

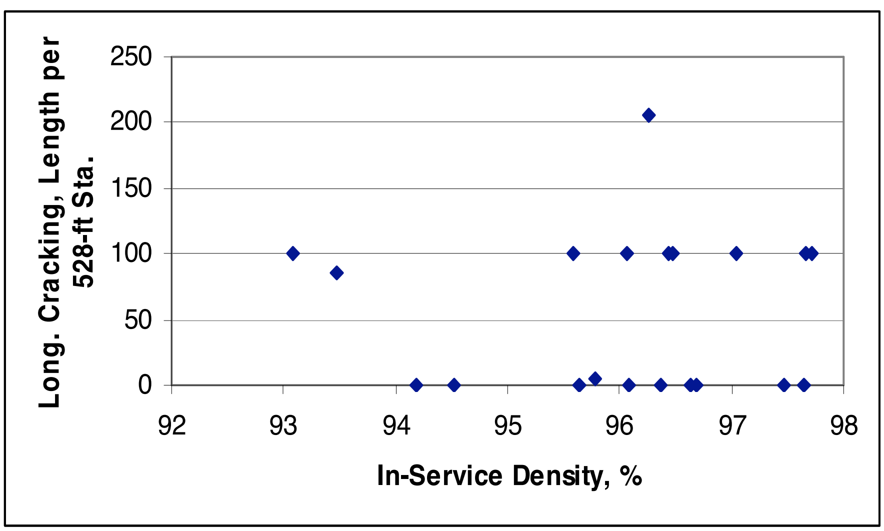

Figure 6.12 In-Service Density and Longitudinal Cracking Extent

The presence of edge raveling was plotted against density (see Figures 6.13 and 6.14), and no relationship was observed. Edge raveling occurred across a range of as-built and in-service densities.

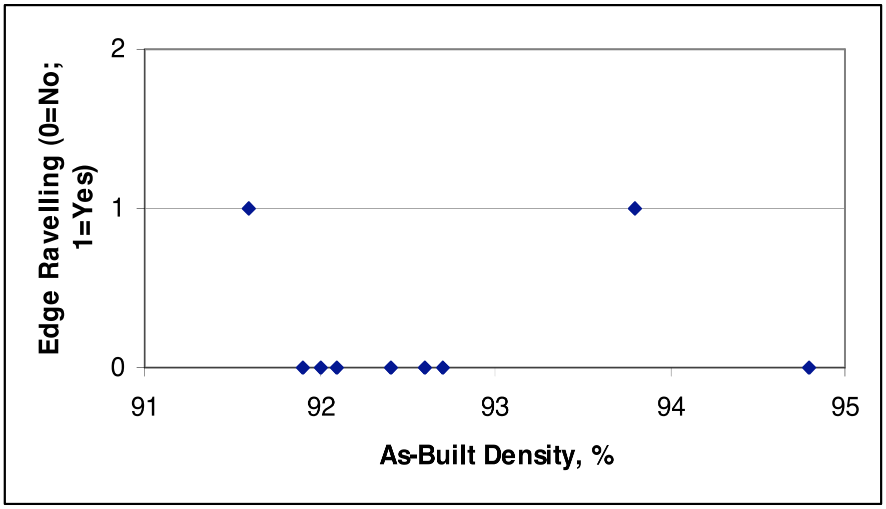

Figure 6.13 As-Built Density and Edge Raveling Extent

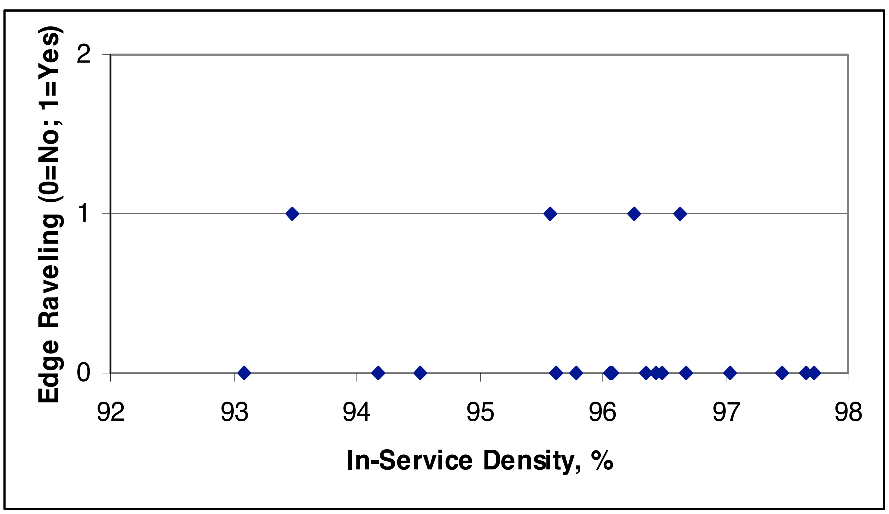

Figure 6.14 In-Service Density and Edge Raveling Extent

Based on the results of Figures 6.1 through 6.14, the PDI index and extent of both transverse and longitudinal cracking were related to as-built pavement density, while there was no relationship between in-service density and the range of performance measures, including the PDI and individual distresses.

6.3.2 Performance and Permeability

In this section, the relationship of permeability and performance was investigated. The 8 permeability measurements in each 0.1-mile test section were averaged to produce a single value. The same approach from the previous section began by evaluating the PDI and individual distresses. First, Figure 6.15 illustrates PDI versus water permeability, where a downward trend was observed when a datapoint of 4.0 x 10E-5 cm/sec was included in the plot. However, without this influential datapoint, no definitive trend existed. Rut depth did not have a definitive relationship with permeability, as illustrated in Figure 6.16.

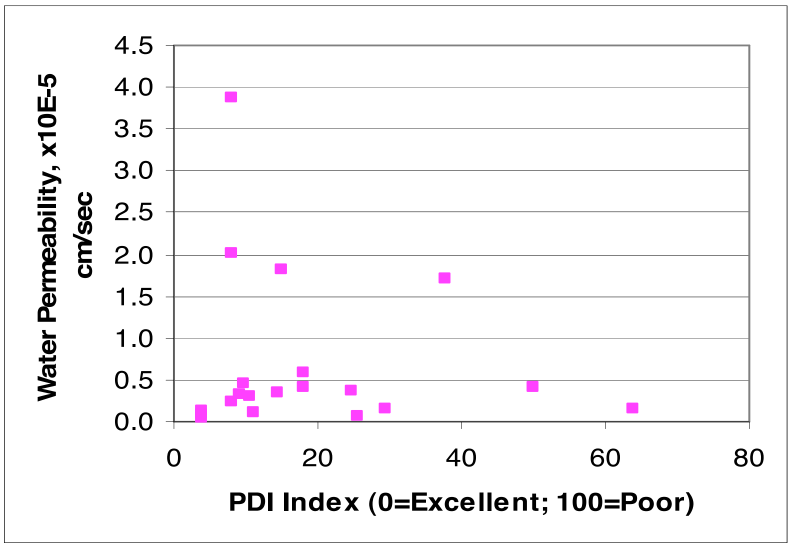

Figure 6.15 Water Permeability and Pavement Distress Index

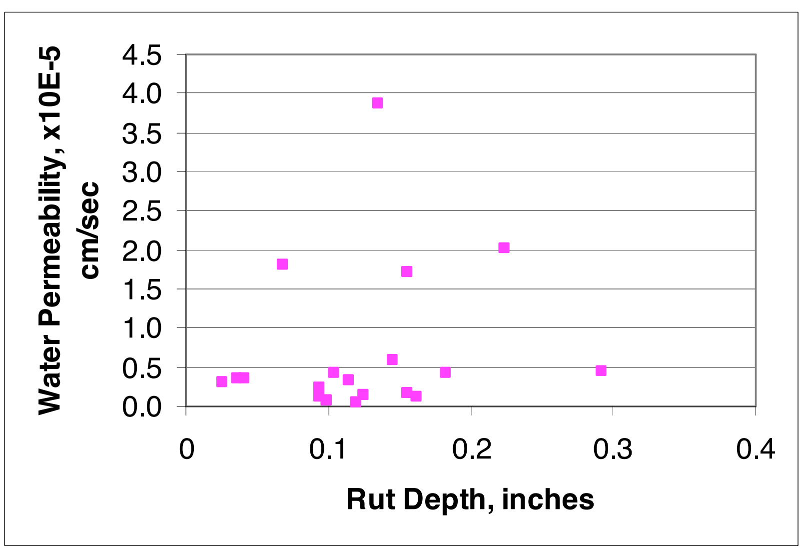

Figure 6.16 Permeability and Rut Depth

Transverse cracking extent and severity were plotted against permeability, as illustrated in Figures 6.17 and 6.18, respectively. In both cases, no relationship was found.

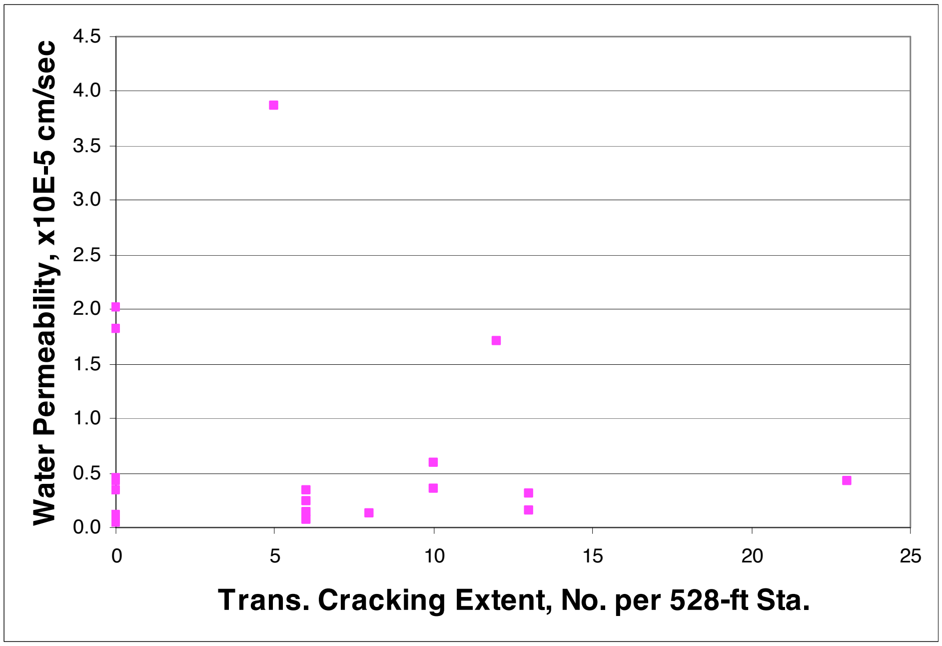

Figure 6.17 Permeability and Transverse Cracking Extent

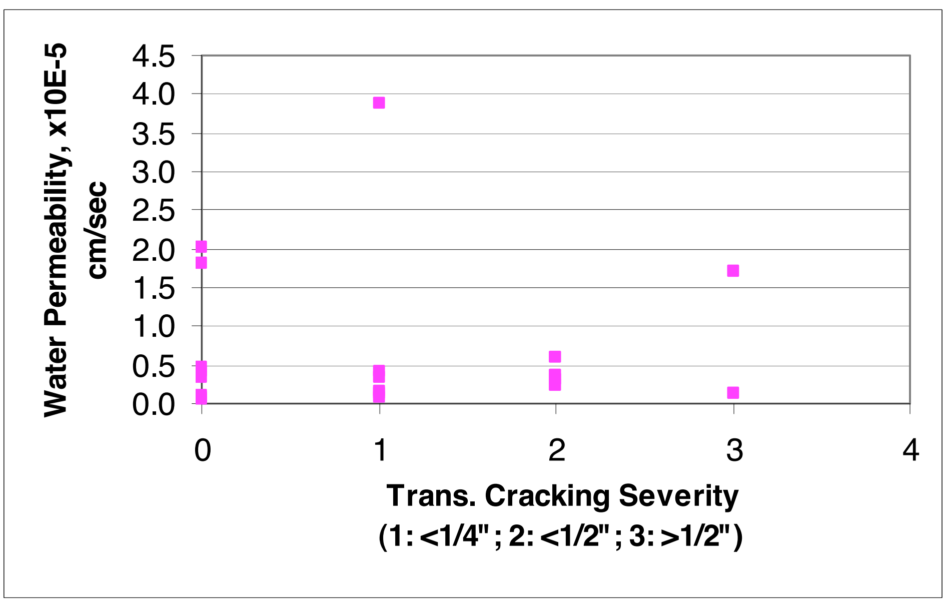

Figure 6.18 Permeability and Transverse Cracking Severity

Similar plots were constructed for longitudinal cracking extent and severity, as shown in Figures 6.19 and 6.20, respectively. Water permeability did not have an effect on longitudinal cracking based on the available data.

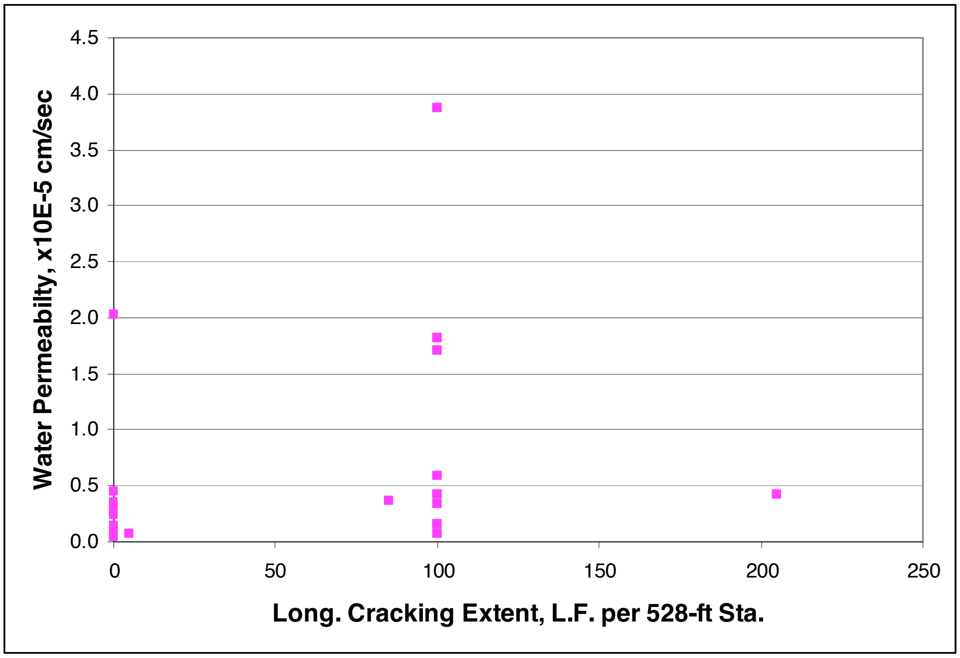

Figure 6.19 Permeability and Longitudinal Cracking Extent

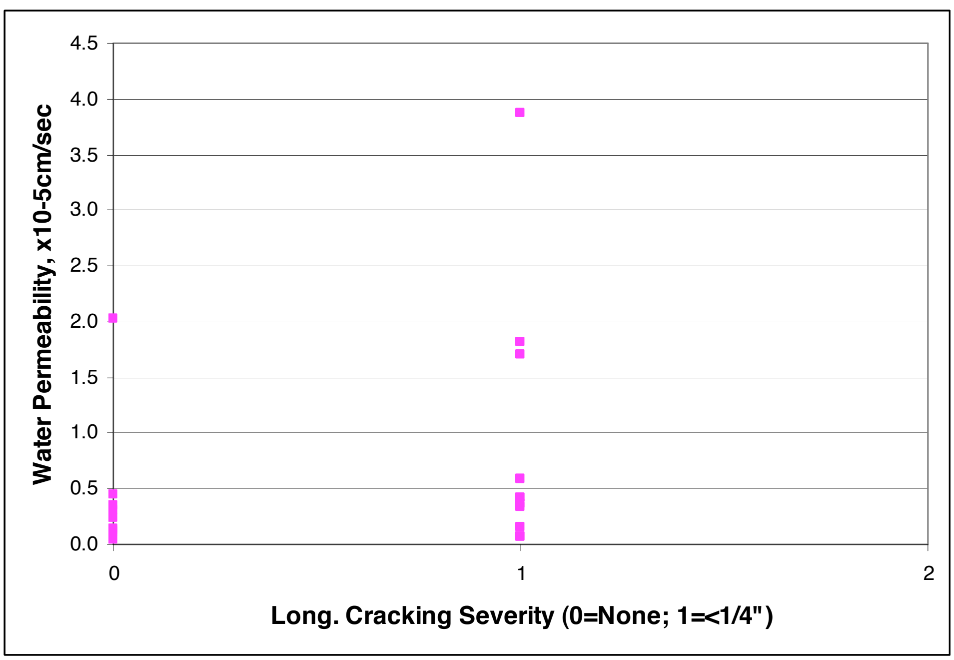

Figure 6.20 Permeability and Longitudinal Cracking Severity

Finally, Figure 6.21 plots edge raveling versus permeability, where permeability values were scattered in the presence of no edge raveling.

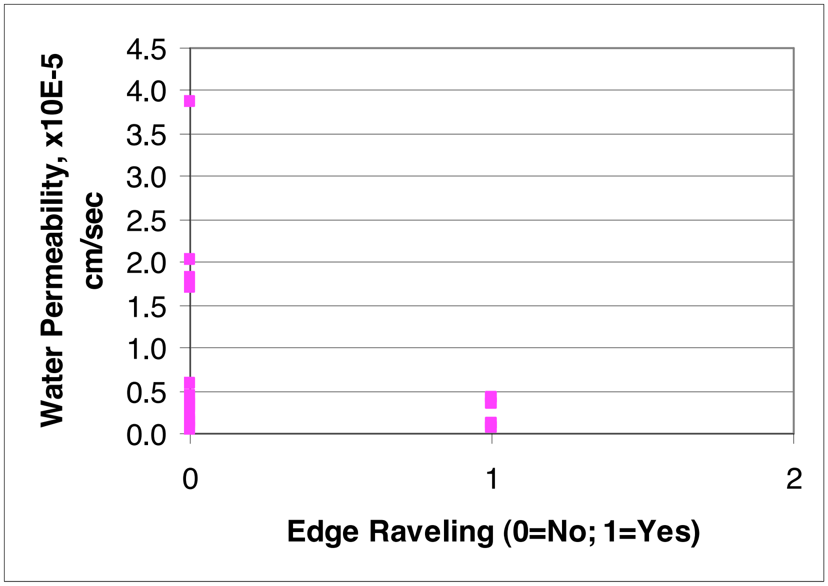

Figure 6.21 Edge Raveling and Permeability

6.4 Analysis of Project Variables and Permeability

To broaden the understanding of water permeability with project and mixture-specific variables, several plots were created and investigated. Beginning with Figure 6.22, age did not directly influence permeability. Pavements 6 years of age were more permeable than 3- and 4-year old pavements – a possible cause may have been from initial Superpave implementation (different compaction techniques, tender zone, gradation, etc.). Higher traffic levels appeared to reduce permeability, as shown by plots for AADT and ADTT in Figures 6.23 and 6.24, respectively.

Figure 6.22 Water Permeability and Pavement Age

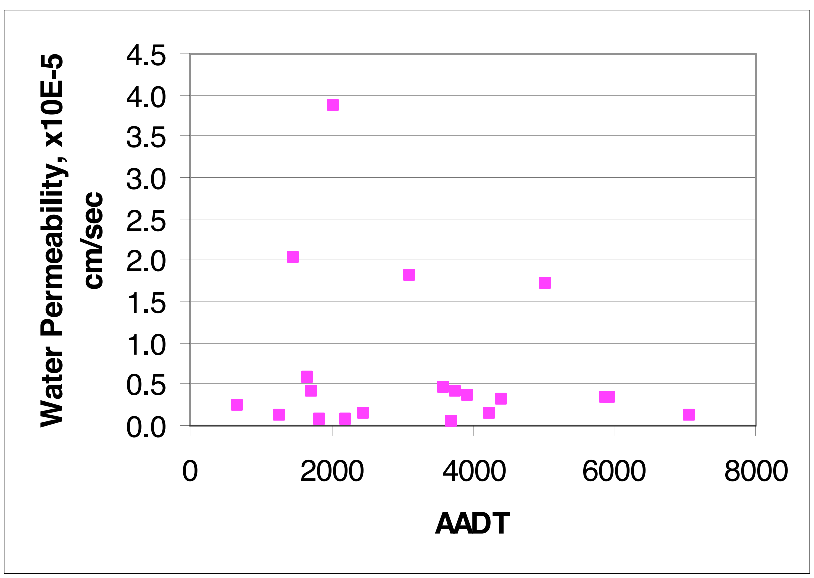

Figure 6.23 Water Permeability and Average Annual Daily Traffic

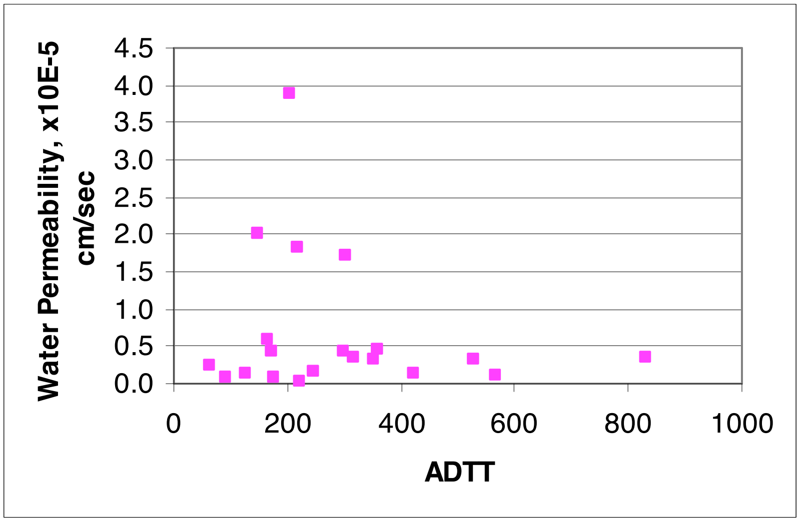

Figure 6.24 Water Permeability and Average Daily Truck Traffic

Passing the 75-um sieve had a correlation (Table 6.1), but Figure 6.25 indicates that 1 data point may have had substantial influence on developing a slight downward trend. But, based on the visual analysis, it appeared that the percentage passing 75-um sieve did not impact permeability.

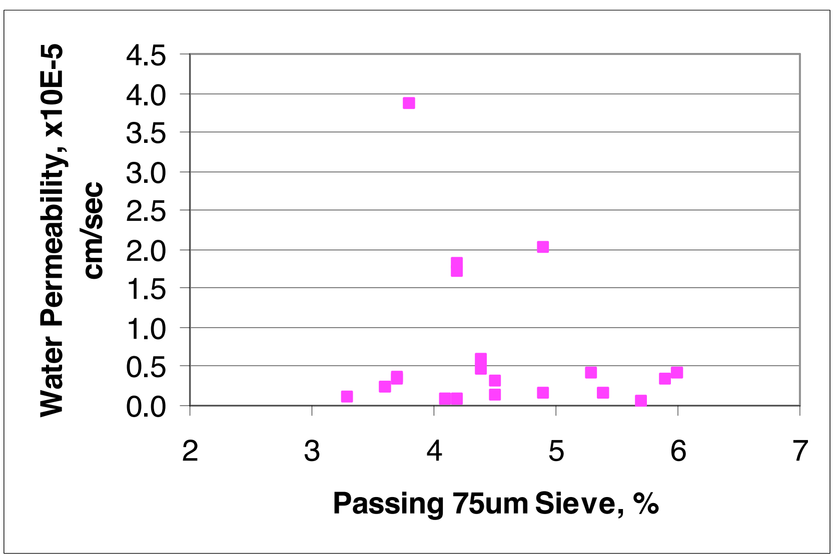

Figure 6.25 Water Permeability and Passing 75um Sieve

Aggregate angularity has been suggested by the previous WHRP study to affect water permeability (Russell et al. 2004). Figure 6.26 and 6.27 respectively illustrate the effect of manufactured sand (as percentage of aggregate blend) and fine aggregate angularity (FAA). Blend percentage of manufactured sand did not appear to have a definitive trend, however, a positive relationship between water permeability and FAA was disclosed. A concern of Figure 6.27 was the sample size of n=5, however, it was observed with the available data that a possible relationship did exist.

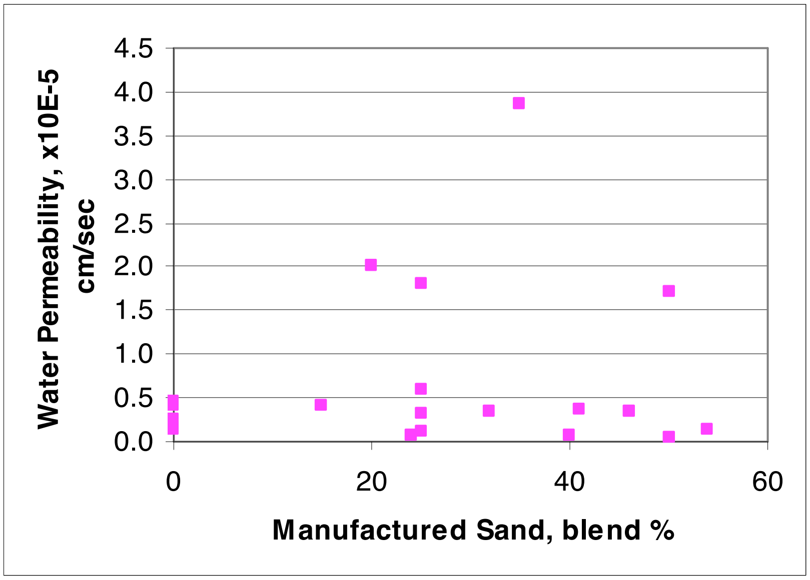

Figure 6.26 Water Permeability and Manufactured Sand Blend Percentage

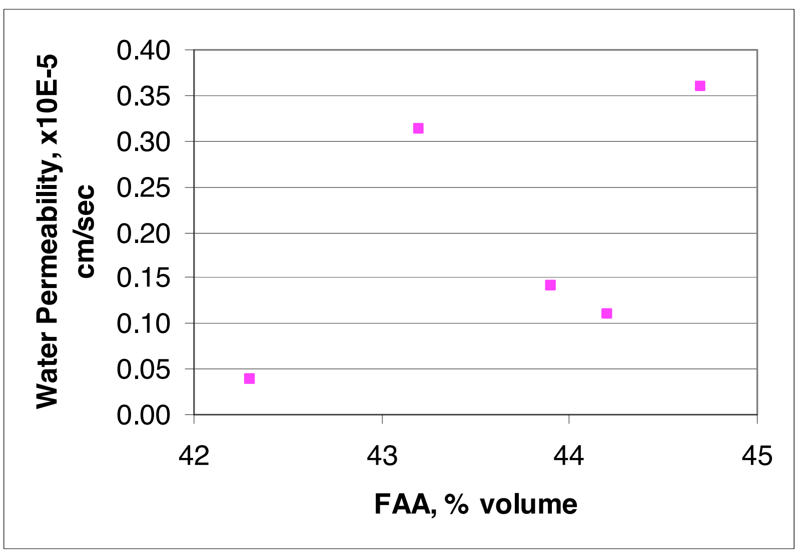

Figure 6.27 Water Permeability and FAA

In-place air voids (density) has been proven to affect permeability in some mixtures, thus design air voids were investigated as a potential variable affecting water permeability. In Figure 6.28 the plot indicated that pavements designed at both 3.5% (pre-Superpave) and at 4% (current practice) had no effect. Voids in mineral aggregate (VMA) had a positive relationship with permeability (Figure 6.29). With the absence of one data point with VMA < 14%, a positive relationship existed.

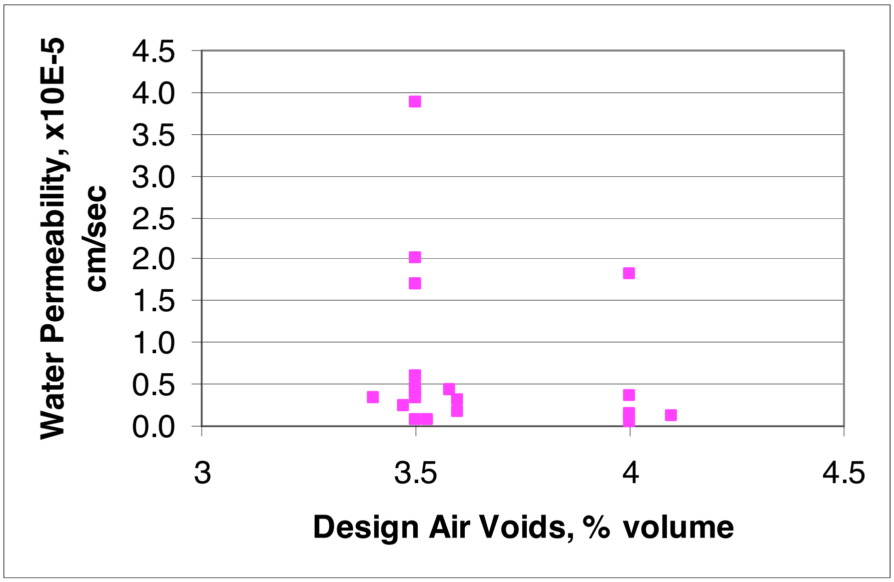

Figure 6.28 Water Permeability and Design Air Voids

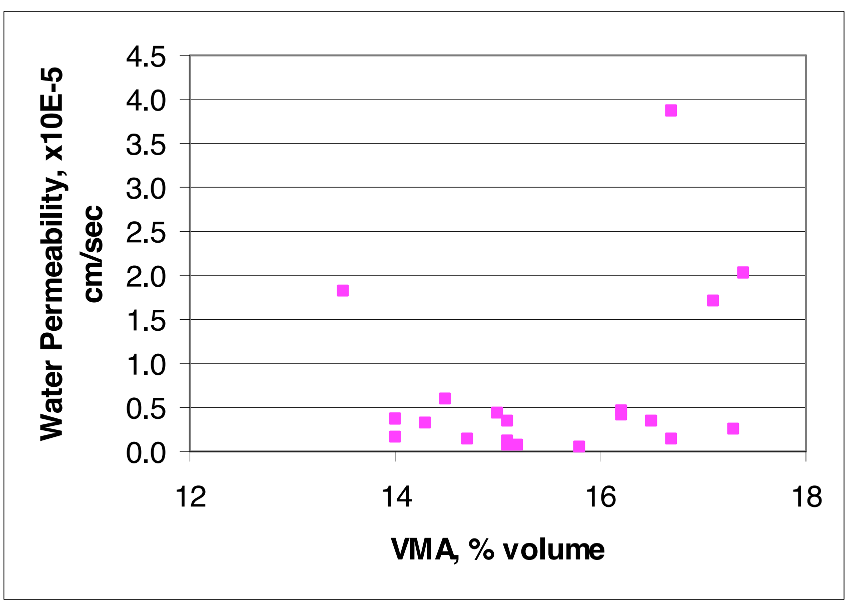

Figure 6.29 Water Permeability and Design VMA

Another important mixture volumetric, voids filled with binder (VFB), was plotted against permeability in Figure 6.30, and no relationship was found. Number of gyrations (Superpave) and number of hammer blows (Marshall) were plotted in Figure 6.31. Type-MV Marshall-designed mixes were designated Ndes = 50. Despite one data point having Ndes = 50 and k = 4 x 10E-5 cm/sec, it appeared that Ndes did not have an affect on permeability.

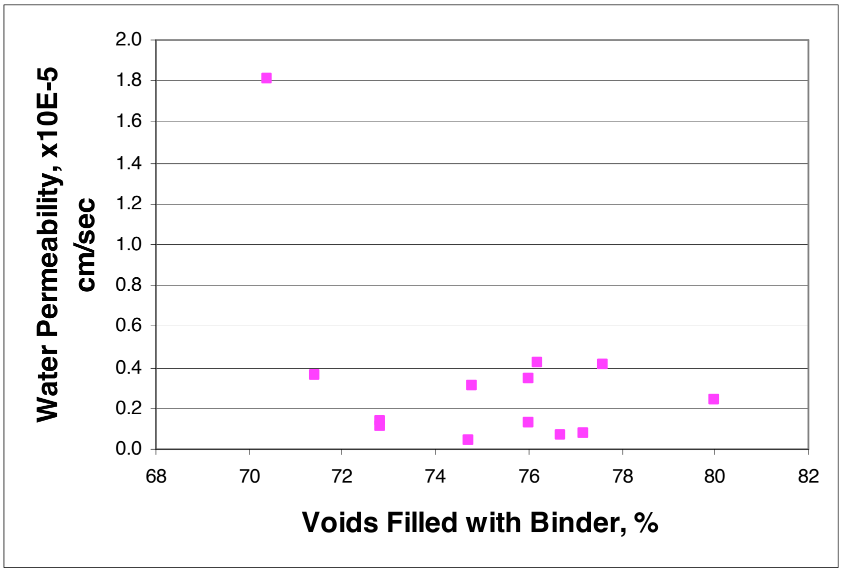

Figure 6.30 Water Permeability and Design VFB

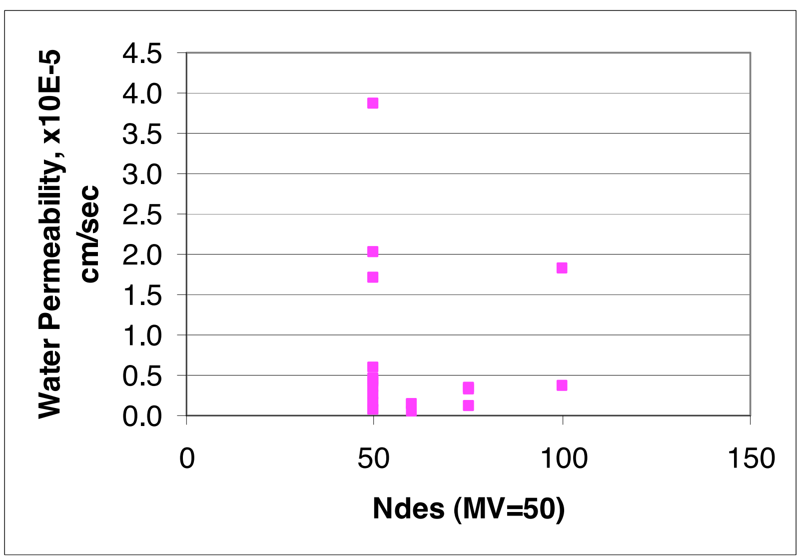

Figure 6.31 Water Permeability and N-Design

Finally, Figure 6.32 compared design asphalt content (AC) with permeability and no distinguishing relationship was observed. Permeability values of 2 x 10E-5 cm/sec were offset at both low and high AC levels. An argument could be made that higher-AC mixes should fill more internal void structure and reduce permeability, however, based on the available data, Figure 6.32 did not support that argument.

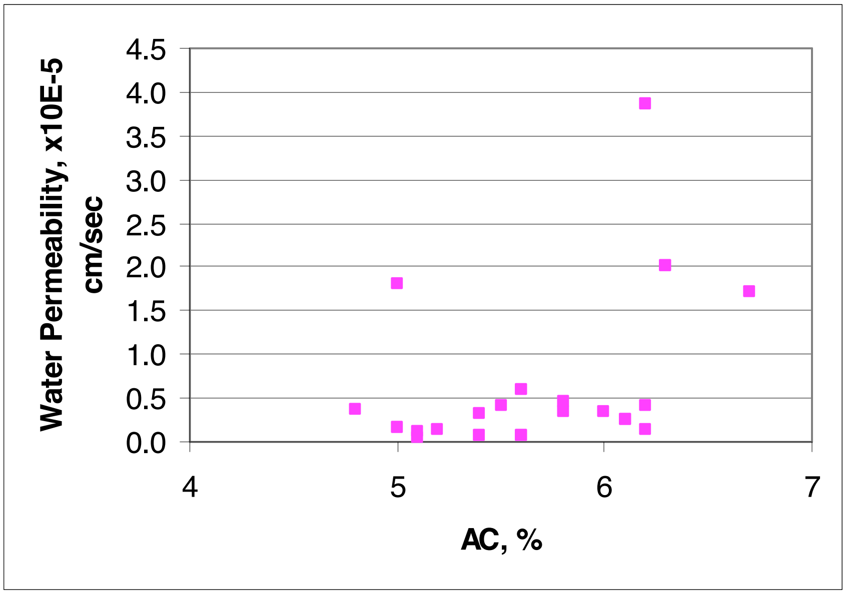

Figure 6.32 Water Permeability and Asphalt Content

6.5 Analysis of Projects for Previous Permeability-Density Study

Two projects from the 2002 WHRP permeability-density study were tested to understand the change in both permeability and density after traffic loading and aging. Several projects in the original study where surface layers were tested included STH 21 near Omro, STH 23 near Montello, USH 8 near Rhinelander, and USH 10 frontage road near Winneconne, Wisconsin Avenue and IH 894 in Milwaukee, and USH 20 Bypass around Rockford, Illinois. It was decided to test STH 23 and USH 8 since it was possible to pair these higher-performing projects with other projects having lower performance and similar traffic levels.

Figure 6.33 plots water permeability at both the time of construction and after 3 or 4 years of traffic. Permeability values dropped from 41 and 188 x 10E-5 cm/sec on the STH 23 and USH 8 projects, respectively, to nearly impermeable values in 3 to 4 years. After a few years of traffic, and infiltration of fine particles and general road grime, these pavements were determined to be nearly impermeable.

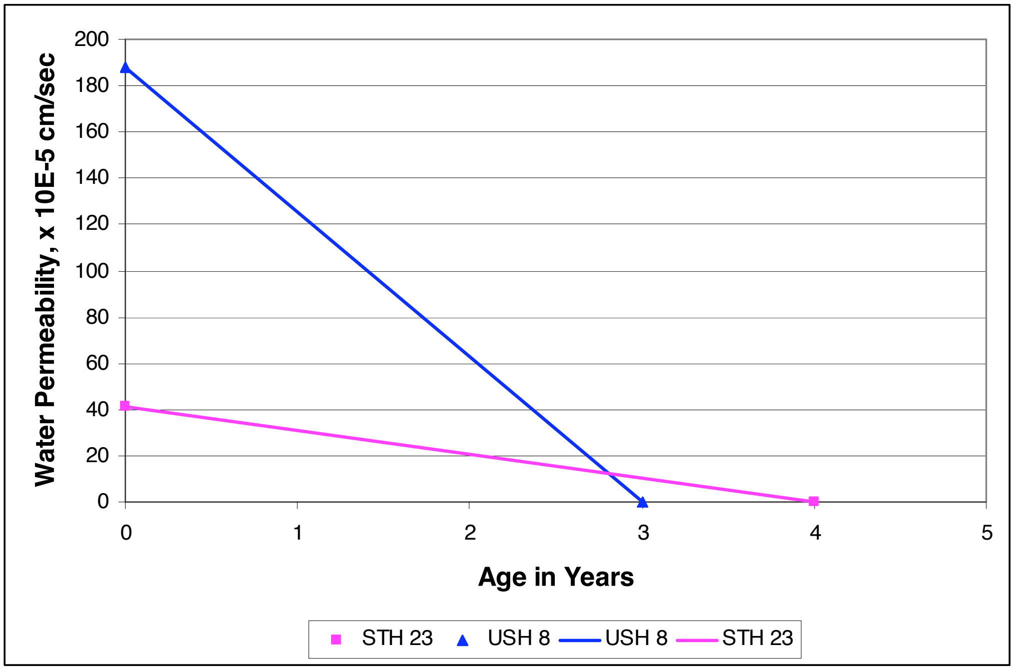

Figure 6.33 Relationship of Water Permeability and Age

6.6 Summary

Data analysis in this chapter produced the following results:

Density

- Pavements having a lower as-built density, generally below 92%, had a lower pavement performance as measured by higher PDI values and more cracking.
- No clear relationship was observed for PDI and in-service density.
- No definitive trend was found between rut depth and both as-built and in-place density. Also, no clear delineation between wheel path location and in-service density could be found. Most rut depths were relatively low.
- No relationship could be found between transverse cracking extent for in-service density.
- There appeared to be greater longitudinal cracking extent at lower as-built densities of about 92%, and no relationship was observed across a wide range of in-service densities.
- No relationship was found between edge raveling and both as-built and in-service density.
- Median in-service density was 96%, indicating that current Ndes levels for mixture design are appropriate.

Permeability

- In general, air and water permeability rates were very low, not exceeding 25 x 10E-5 cm/sec with the air permeameter and 15 x 10E-5 cm/sec with the water permeameter. Except for 2 out of 160 test sites, water permeability values were less than 5 x 10E-5 cm/sec, thus the pavements were nearly impermeable.
- There was no definitive relationship between permeability and performance.
- Rut depth did not have a definitive relationship with permeability.
- No relationship was found between permeability and both transverse cracking extent and severity.
- Water permeability did not have an effect on longitudinal cracking and edge raveling based on the available data.
- Age did not directly influence permeability. Pavements 6 years of age were generally more permeable than 3- and 4-year old pavements.
- Higher traffic levels, as measured by daily vehicle traffic and daily truck traffic, appeared to reduce permeability.
- Percentage passing 75-um sieve had no impact on permeability.
- Blend percentage of manufactured sand did not appear to have an effect trend on permeability, however, a positive relationship between water permeability and FAA was disclosed. A concern of the FAA determination was the sample size of n=5, however, it can be concluded with the available data that a relationship did exist.
- Pavements designed at both 3.5% design air voids (pre-Superpave) and 4% air voids (current practice) had no effect on permeability.
- Voids in mineral aggregate (VMA) had a significant positive correlation with permeability.
- Voids filled with binder (VFB), Ndes, and asphalt content did not have an affect on permeability.

CHAPTER 7 DEVELOPMENT OF CRITERIA FOR PERMEABILITY AND DENSITY

7.1 Introduction

The previous chapters investigated the relationship of permeability, density, performance, and mixture variables. In this chapter, a methodology for developing design criteria for permeability and density is presented based on preliminary findings. These relationships were examined through a series of hypothesis statements as summarized below and discussed in the following sections:

a) Mix design properties dictate to some extent the final as-built density achieved at time of construction;
b) The as-built density dictates the future performance of the pavement - higher as-built densities result in better pavement performance as measured by the PDI;
c) Similarly, higher as-built densities result in less permeable pavements; and
d) Less permeable pavements exhibit better overall performance as measured by the PDI.

7.2 Mix Design Properties and As-built Density Relationships

A preliminary analysis involving data plots and simple regression was conducted to examine key mix design variables that influence as-built density. Nine projects (out of twenty) with an average age of 4.8 years had available as-built density data. Using these projects, two key variables including the design truck traffic (a surrogate for mix type) and the VFB were identified to influence the as-built density. The relationships between truck traffic and as-built density, as well as VFB and as-built density are shown respectively in Figures 7.1 and 7.2. Figure 7.1 suggests that as-built density achieved at time of construction appears to decrease non-linearly with increased truck traffic level. This observation may be due to the fact that higher traffic levels generate thicker pavements in design, and may be difficult to compact compared to thinner pavements, which are associated with lower traffic levels. The model representing the relationship shown in Figure 7.1 is represented as Model #1 in Table 7.1.

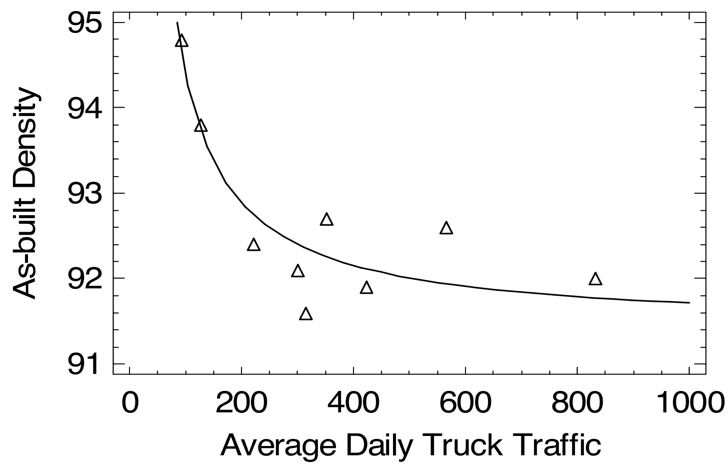

Figure 7.1 As-built Construction Density versus Truck traffic

Table7.1 Model Characteristics

Model #	Model Form	Standard Error of Estimate	F-Ratio	P-Value	R-squared, %
1	r_0=91.4199 + 293.524/ADTT	0.4704	30.9	0.0008	81.6
2	r_0=62.2908 + 0.408718*VFB	0.7631	7.8	0.0312	56.6
3	PDI/year_= 1/(-33.0673 + 0.36269* r_0)	0.2753	14.5	0.0066	67.5
4	K_w =1/(-252.41 + 2.78521* r_0)	2.8166	8.1	0.0290	57.6
5	PDI/year = -0.475181 + 4.63626* $(K_w)^{0.5}$	1.6768	6.5	0.0434	52.0

r_0 = As-built density
ADTT = Average Daily Truck Traffic
VFB = Voids filled with bitumen
K_w =Water permeability

Figure 7.2 shows higher VFB resulted and in higher as-built density. The relationship is depicted as Model #2 in Table 7.1.

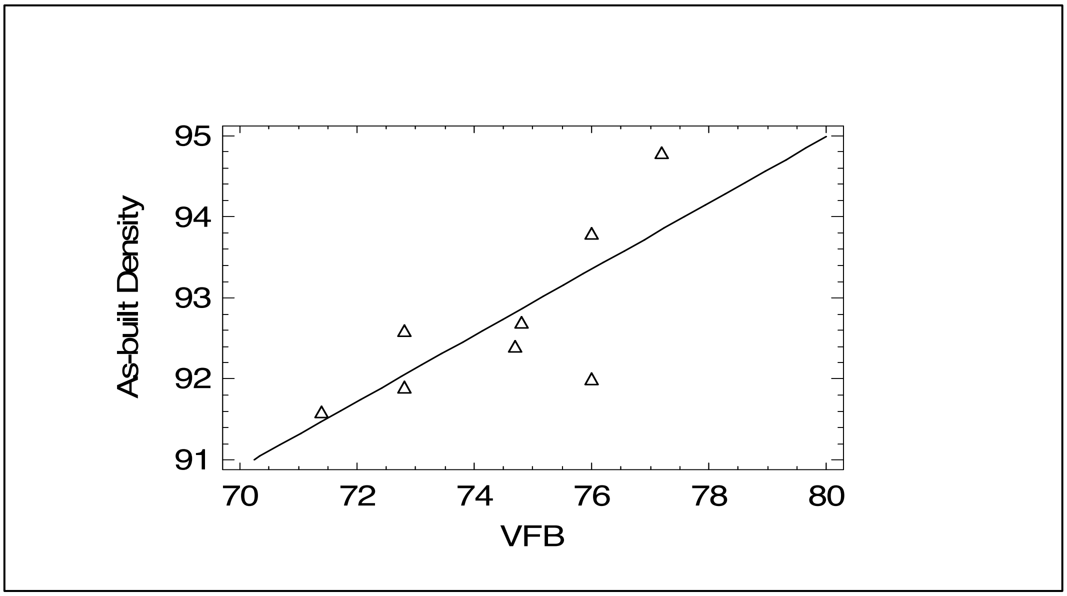

Figure 7.2 As-built Density and VFB Relationship

7.3 Performance and As-built Density Relationship

The relationship between as-built density and performance (as indicated by the PDI/year) is shown in Figure 7.3 and represented as Model #3 in Table 7.1. Figure 7.3 suggests that pavements with high as-built densities tend to exhibit better performance.

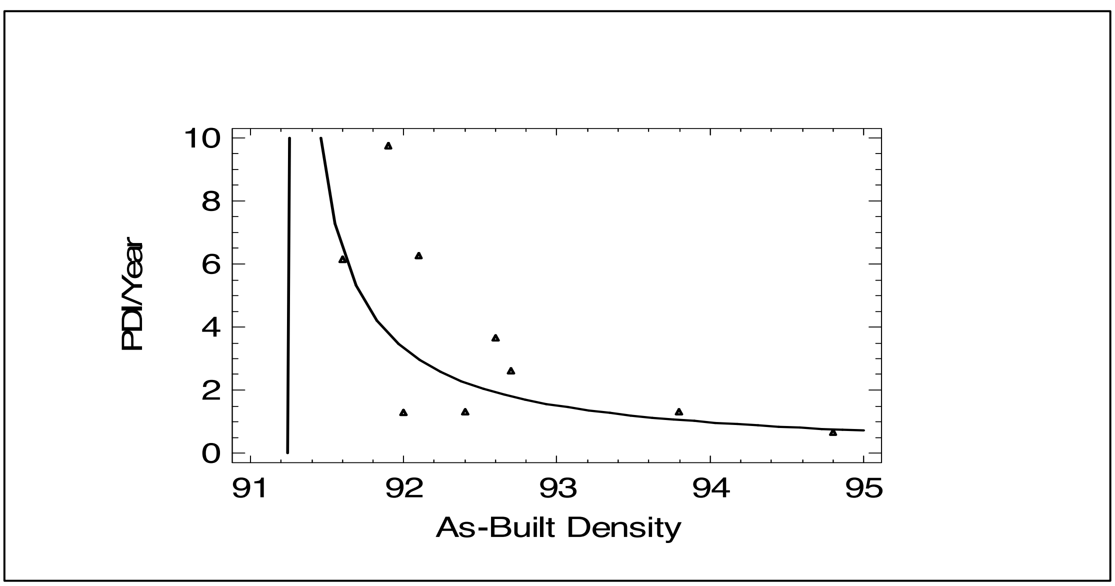

Figure 7.3 Pavement Performance and As-built Density Relationship

7.4 Permeability and As-built Density Relationship

Figure 7.4 shows the relationship between as-built density and in-service water permeability. This relationship is represented in Table 7.1 as Model #4 and supports the hypothesis that higher as-built densities result in less permeable pavements.

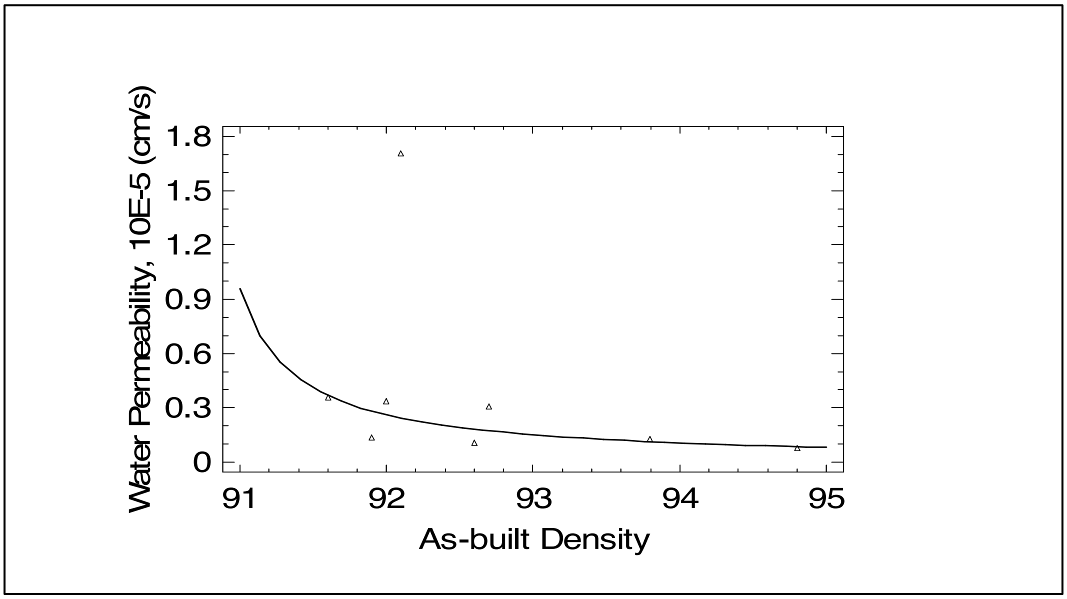

Figure 7.4 Water Permeability and As-built Density Relationship

7.5 Performance and Permeability Relationship

Figure 7.5 shows the relationship between performance and water permeability. This relationship is represented as Model #5 in Table 7.1. Figure 7.5 suggests that water permeability increases in a non-linear fashion with increasing pavement deterioration.

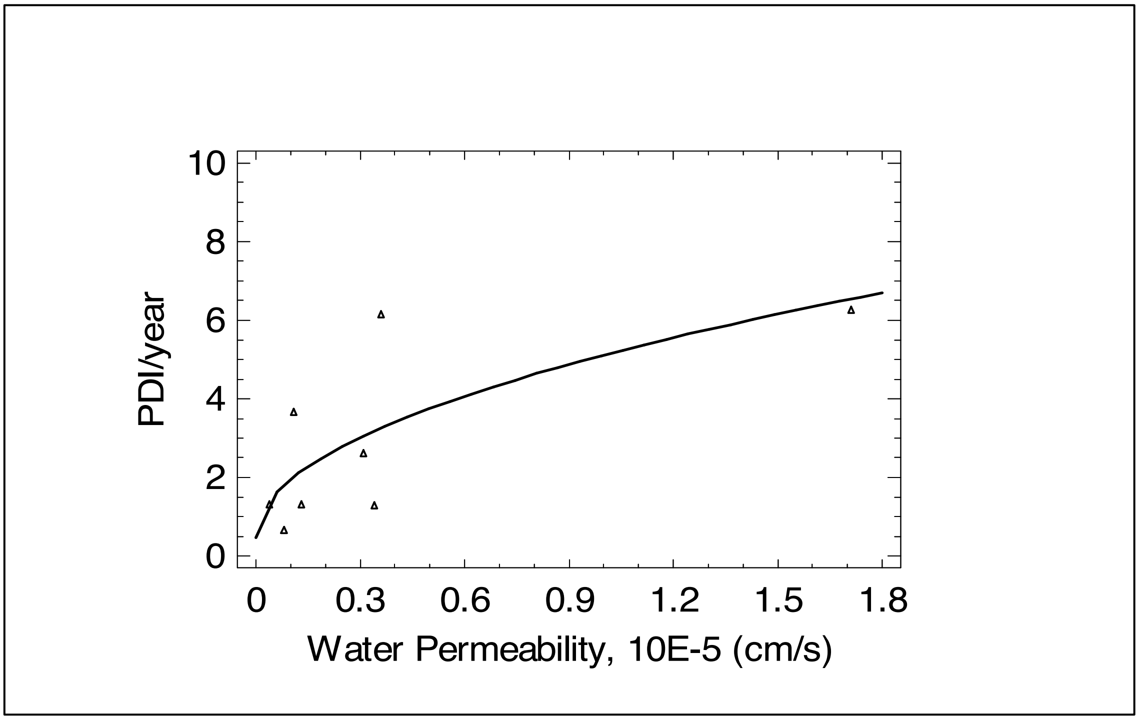

Figure 7.5 Pavement Performance and Water Permeability Relationship

7.6 Models Application and Criteria

The application of the models described in the previous subsections is summarized in the framework shown as Figure 7.6. A design or target PDI is initially selected to determine the expected design permeability, K_1, which in turn is used to specify the as-built density at construction, ρ_{01} to achieve K_1. Similarly, the design or target PDI is used to determine the as-built density, ρ_{02} to achieve the target value. The maximum of the two values is chosen as the controlling density to yield the desired PDI and corresponding design permeability. The controlling density is further used to select the critical mix design property as represented, for example, by the VFB.

The framework shown in Figure 7.6 is illustrated in Figure 7.7 using the models presented in Table 7.1. In this illustration, a desired PDI/year of 4.0 is assumed as the target PDI/year for preventive maintenance intervention. Using Figure 7.7, an as-built density of 91.5% is triggered for the target PDI/year of 4.0 with a corresponding expected water permeability of 0.60x10E-5 cm/s. A density of 91.8% is also required to achieve the desired PDI/year of 4.0. Hence, the controlling density to satisfy permeability and PDI requirements is the latter value (91.8%), which is the greater of the two. The corresponding VFB based on the density is approximately 72%.

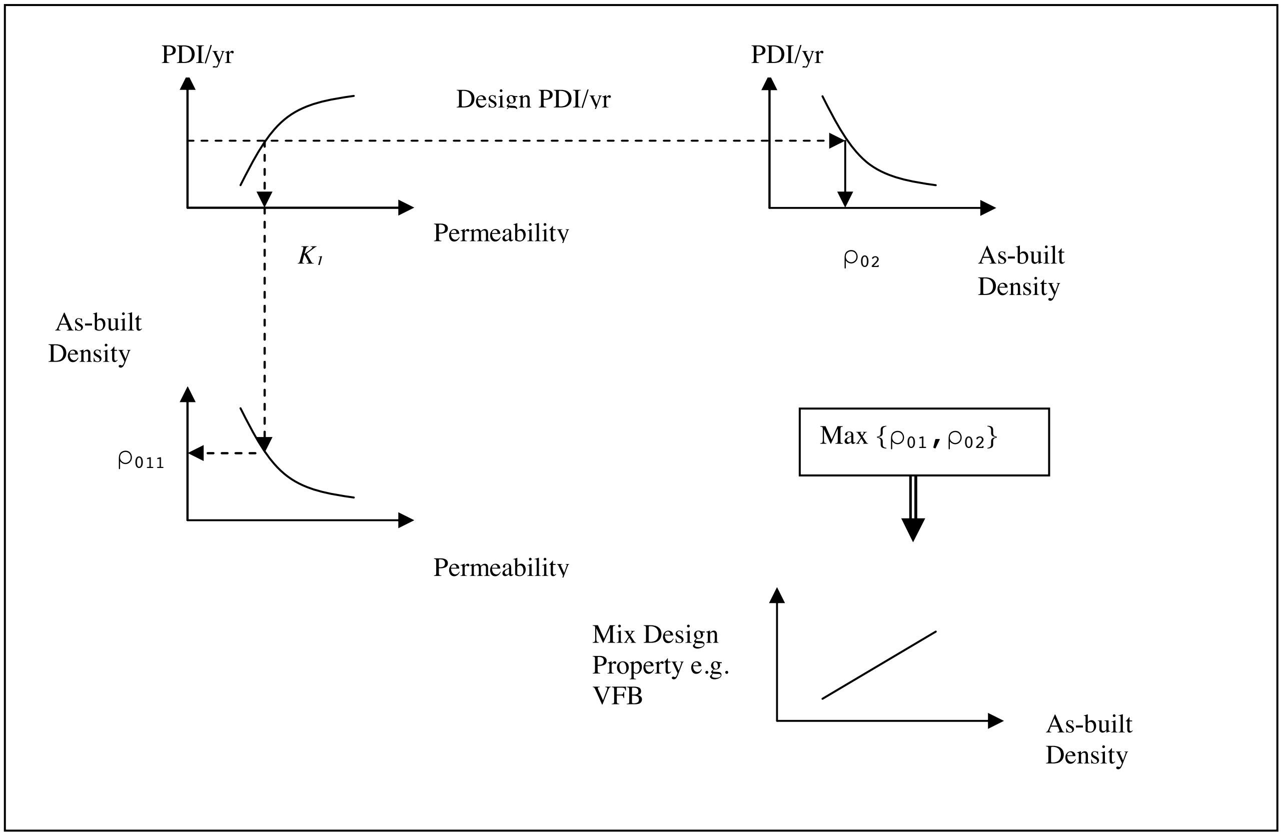

Figure 7.6 Framework for Relating Permeability and Mix Design Properties to Performance

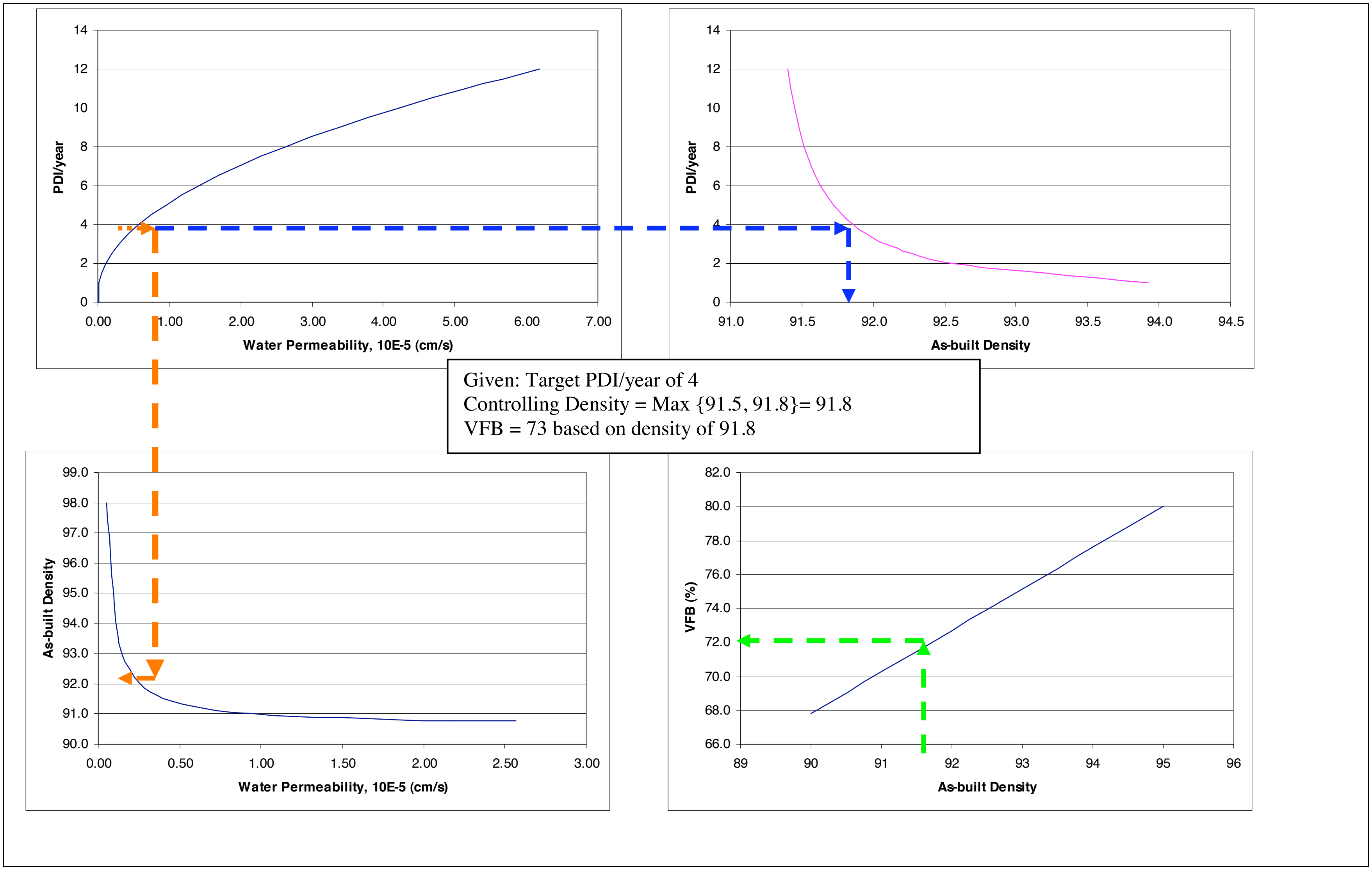

Figure 7.7 Application Model for Relating Permeability and Mix Design Properties to Performance

7.7 Recommendations for Establishing True Design Criteria

A concern of applying the criteria framework in the previous section to determine new design criteria for density and permeability, was lack of relating true permeability values at construction with actual performance. Useful information about in-service permeability and density was acquired during this study, however, to translate the data to determine new criteria is not warranted at this time. The models in Table 7.1 have sufficient accuracy, as measured by the R-squared statistic, however, the true relationship between as-built permeability and current performance is lacking.

If criteria are to be established, a data set is needed that truly ties as-built construction properties with performance. The data set should also have the capability to be stratified by unique indigenous materials and project characteristics within various regions of the state, and yield consistent results for design criteria. For example, the data may find that a minimum as-built density of 93% is needed during construction to ensure a certain performance level at 10 years of pavement age (say, a target PDI of 30). This relationship would better predict maintenance intervention during the life of the pavement, and aid in more accurate life-cycle cost analysis. Contractors may want to consider certain VFB and asphalt content combinations, for example, to assist in achieving the compaction. Current Ndes levels could be calibrated against the in-service density at 4, 7, or 10 years of age (data currently suggest that the levels are sufficient).

Thus, in Phase II of this study, it is recommended that an experiment be designed from findings from Phase I to generate data capable of producing performance models robust to a broad range of projects, that in turn will establish specific criteria to be published in construction and materials specifications. Project data from the original WHRP study would be used in the Phase II investigation. The framework presented in this report will assist in determining the specific thresholds. This effort will require a long-term study of about 5 years in duration.

In Phase II of the study, the following specific components are recommended for the experimental design and work plan approach, by year:

<u>2006</u>

1. Collect a list of all HMA projects constructed in the past two years (2005 and 2006). Stratify each year by Design ESALs (0.3, 1, 3, 10, 30 and 30X) and record the sample size. This sample will estimate anticipated projects in 2007 and 2008.
2. Begin developing a list of projects to be constructed in 2007, and stratify each by basic project attributes, such as Design ESALs, base type (CABC, rubblized, etc.), base density required (90.5%, 91.5%, etc.), general location to anticipate aggregate source (limestone, gravel, etc.), tonnage, new construction versus overlay, mill-and-fill versus pulverize, etc. This list will help determine whether 2 consecutive years of projects (2007 and 2008) are needed for performance evaluation.

3. Conduct a laboratory study of collected cores to investigate directional flow of water and permeability before and after removing fine particles. The laboratory experiment would evaluate if surfaces pores are clogged with sand, road grime, and other debris, and if so, the actual permeability can be measured and compared with the performance data set.

<u>2007 (time=0)</u>

1. Identify all projects for paving and stratify by Design ESALs and density required per layer.
2. Access MetaManager and PIF databases to collect all data about these projects. Although Design ESALs provide a surrogate for design traffic levels, specific traffic and truck levels are needed for project selection.
3. Select projects having a range of required densities. This step is critical since different levels in density are necessary to understand the response in permeability and performance.
4. Obtain project plan sets for all selected paving projects.
5. Overlay Reference Points (or Sequence Number) from PIF database across project stationing to determine viable test sections for a 0.1-mile field test section.
6. Coordinate with WisDOT, contractors, and consultants for field testing. Testing will be performed within furnished project traffic control to minimize study costs.
7. Test HMA projects in 2007 paving season having at least 2 RPs (approximately 2 miles in length). A project with at least 2 RPs should have sufficient tonnage to have an opportunity to allow a JMF change and produce a near steady-state in material properties.
8. On each project, test all layers for water permeability and density. Select two 0.1-mile segments for testing per layer based on paving schedule for that project. Randomly sample n=10 test sites within each of the two 0.1-mile segments for each layer. This will yield n=2 test segments within a project, and strengthen the comparison between density/permeability and performance by having 2 subsamples per project, and a total of 20 sites per layer. This approach will also allow flexibility in moving the field test segments on the project to avoid conflict with paving crews and other issues. To minimize re-mobilization to a project, test a lower layer the day before, or morning of, upper layer paving. Consider testing near the longitudinal joint and both shoulders and mainline for a single mix type.
9. Perform air permeability and density "growth" testing between roller passes to understand change in permeability with density.
10. Cut 5 cores per project layer for permeability calculations, and to adjust the nuclear density gauge to core density, as was done in this study. Consider the use of GPS to pin-point test segment location for future evaluation testing.
11. Record month of paving to understand densification from traffic during seasonal changes.
12. Synthesize the data and report the findings to WHRP and publish.

2009 (time=2 years)

1. Collect performance data from PIF database and begin performance monitoring. A request would be made more frequent performance testing as necessary.
2. Collect MetaManager traffic data.
3. Note – by 2009, WisDOT will have a full-integrated HMA database relating design, construction, environmental, traffic, and performance data. This database, now named the Pavement Performance Analysis System (PPAS), will be developed by UW-Platteville in cooperation with WisDOT and industry partners through the Midwest Regional University Transportation Center (MRUTC).

2011 (time=4 years)

1. Measure in-service density on each project segment using nuclear density gauge, and offset nuclear readings with 5 cores. (Patched core holes from 2007 will help confirm 0.1-mile test segment location). Also, conduct a manual performance distress survey. Water permeability tests will not be conducted since this study has confirmed there in minimal permeability after pavement is placed in service. These activities will require traffic control, and a plan would be developed to minimize traffic control costs with county highway departments, or an alternate means.
2. Collect performance data from PIF database and begin performance monitoring.
3. Collect MetaManager traffic data.
4. Conduct initial performance modeling to density and permeability criteria.
5. Perform a fatigue analysis on cores for those projects having significantly more distress (rutting, cracking, raveling, etc.). Consider new advancements in indirect tensile strength procedures to more realistically characterize pavement fatigue.
6. Model the data to determine density and permeability criteria.

In closing, Phase II will require considerable time and resources that deviate from normal WHRP practices. However, the scope of this work will allow WisDOT and partners to develop true criteria across a broad range of HMA paving projects. Since this state does not have full-scale testing facilities such as MnRoads, WesTrack, or the NCAT Test Track, this study provides an alternate means by using in-service pavements as the laboratory. This approach will allow the state to move towards true performance-based criteria for HMA pavement research and development, and other tangential benefits as the project progresses.

7.8 Summary

This chapter presented a methodology for developing design criteria for permeability and density based on preliminary findings. First, plots and models were developed between variables. Two key variables that influenced the as-built density included the design truck traffic (a surrogate for mix type) and the VFB, where as-built density achieved at time of construction appears to decrease non-linearly with increased truck traffic level.

Performance models were developed as well, and it was shown that pavements with higher as-built densities tend to exhibit better performance (as indicated by the PDI/year). As an example, to achieve higher as-built density, higher VFB designs may assist in compaction. Higher as-built densities result in less permeable pavements, and water permeability increases in a non-linear fashion with increasing pavement deterioration.

The application of the models presented in this chapter were used to develop a criteria framework. Defining a specific criteria requires establishing a target PDI (as defined by preventive maintenance intervention, economic analysis, or other means) to yield an expected design permeability, which in turn specifies as-built density at construction. Similarly, the target PDI/year determines the as-built density, to achieve the target value. The maximum of the two values is chosen as the controlling density to yield the desired PDI and corresponding design permeability. The controlling density is further used to select the critical mix design property as represented, for example, by the VFB. Other mixtures variables can easily be included, once supporting data are available and modeled.

An example was illustrated where as-built density of 91.5% is triggered for the target PDI/year of 4.0 with a corresponding expected water permeability of 0.60x10E-5 cm/s. A density of 91.8% is also required to achieve the desired PDI/year of 4.0. Hence, the controlling density to satisfy permeability and PDI requirements is the latter value (91.8%), which is the greater of the two. The corresponding VFB based on the density is approximately 72%. Although the 0.60x10E-5 cm/s rate is unrealistic and reflects in-service permeability, a similar approach would be used to determine as-built permeability criteria.

Based on limited data, it was not possible to establish definitive criteria for permeability and density. A work plan was proposed for Phase II of the study to produce performance models that will establish specific criteria. Phase II will require a long-term study of about 5 years. As-built construction data will be collected on projects throughout the state having varying density requirements, then performance data are collected and monitoring every other year until the pavement reaches 5 years of age.

CHAPTER 8 CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

Based on the data collected and analyzed in this study, the following conclusions were reached:

Permeability

1. In general, air and water permeability rates were very low. Water permeability rates ranged from 0 to 5 x 10E-5 cm/sec for in-service pavements 3 to 11 years of age, and air permeability rates were a factor of 10 greater than water permeability. Water permeability rates between wheel paths were generally higher than in the wheel paths. In-service pavement density ranged from 92% to 99%.

2. Pavements having a lower as-built density, generally below 92%, had a lower pavement performance as measured by higher PDI values and more cracking. There was no definitive relationship between permeability and performance.

3. No definitive trend was found between rut depth and both as-built and in-place density. Also, no clear delineation between wheel path location and in-service density could be found. Most rut depths were relatively low.

4. Median in-service density was 96%, indicating that current Ndes levels for mixture design are appropriate.

5. Air permeability trended downward with an increase in density, while water permeability had no discernible trend.

6. Age did not influence permeability, where some pavements 6 years of age were more permeable than 3- and 4-year old pavements.

7. Higher traffic levels, as measured by daily vehicle traffic and daily truck traffic, appeared to reduce permeability.

8. Percentage passing 75-um sieve s sieve had no impact on permeability.

9. Blend percentage of manufactured sand did not appear to have an effect trend on permeability, however, a positive relationship between water permeability and FAA was disclosed. A concern of the FAA determination was the sample size of n=5, however, it can be concluded with the available data that a relationship did exist.

10. Pavements designed at both 3.5% air voids (pre-Superpave) and 4% air voids (current practice) had no effect on permeability.

11. Voids in mineral aggregate (VMA) had a significant positive correlation with permeability, while voids filled with binder (VFB), Ndes, and asphalt content did not have an affect on permeability.

12. Rut depth did not have a definitive relationship with permeability. Also, no relationship was found between permeability and both transverse cracking extent and severity.

13. Performance models were developed, and it was shown that pavements with higher as-built densities tend to exhibit better performance (as indicated by the PDI/year). As an example, to achieve higher as-built density, higher VFB designs may assist in compaction. Higher as-built densities result in less permeable pavements, and water permeability increases in a non-linear fashion with increasing pavement deterioration.

14. Defining a specific criteria requires establishing a target PDI to yield an expected design permeability, which in turn specifies as-built density at construction. Similarly, the target PDI/year determines the as-built density, to achieve the target value. The maximum of the two values is chosen as the controlling density to yield the desired PDI and corresponding design permeability. The controlling density is further used to select the critical mix design property as represented, for example, by the VFB. Other mixtures variables can easily be included, once supporting data are available and modeled.

15. An example was illustrated where as-built density of 91.5% is triggered for the target PDI/year of 4.0 with a corresponding expected water permeability of 0.60x10E-5 cm/s. A density of 91.8% is also required to achieve the desired PDI/year of 4.0. Hence, the controlling density to satisfy permeability and PDI requirements is the latter value (91.8%), which is the greater of the two. The corresponding VFB based on the density is approximately 72%.

16. Based on limited data, it was not possible to establish definitive criteria for permeability and density. A work plan was proposed for Phase II of the study to produce performance models that will establish specific criteria. Phase II will require a long-term study of about 5 years. As-built construction data will be collected on projects throughout the state having varying density requirements, then performance data are collected and monitoring every other year until the pavement reaches 4-5 years of age.

8.2 Recommendations

The following recommendations were made from the data and analysis presented in this report, for work in Phase II of this study:

1. Design an experiment to generate data capable of producing performance models robust to a broad range of projects, that in turn will establish specific criteria to be published in construction and materials specifications.

2. Establish target PDI values in the models to yield target design density, permeability thresholds, and mixture components.

3. Include an economic analysis in the PDI definition (i.e., what PDI should trigger rehabilitation, and is the PDI threshold reasonable and practical).

4. Continue to monitor in-service density to verify that Ndes values correlate with in-service density.

5. Use project data from the original WHRP study in the Phase II work plan and investigation.

6. Implement the Phase II work plan. This effort will require a long-term study of about 5 years in duration. Please see earlier chapter for a specific work plan from 2007 to 2011.

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